Fracture resistance and failure mode of layered translucent zirconia with different crown designs

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This study investigated the impact of different veneering design on the fracture resistance and failure mode of layered translucent zirconia crowns, compared to the full monolithic zirconia crowns. Ninety crowns with different designs were divided into six groups ($n=15$); one fully contoured monolithic crown (FMC), one fully veneered with porcelain (FVC), or four partially veneered designs. All crowns were thermo-cycled, and then loaded to failure in a universal testing machine. The fracture resistance (N) and fracture modes were assessed. One-way ANOVA was performed followed by Tukey's multiple comparison ($\alpha<0.05$). Results demonstrated that all the tested partially veneered designs exhibited enhanced fracture resistances and were comparable to that of the full-contour monolithic translucent zirconia crowns.

Keywords: Translucent zirconia, Partially veneered zirconia, Fully veneered zirconia, Monolithic zirconia

INTRODUCTION

All-ceramic crowns and fixed partial dentures became the standard choice for most dentists in the last two decades, with a dramatic decline in the demand for metal-ceramic restorations^{1,2}. The improved esthetic properties of all-ceramic restorations are mainly attributed to enhanced optical properties, especially the improved translucency that made it possible to match and replicate the natural tooth characteristics^{3,4}.

A wide range of ceramic materials has been developed to meet the esthetic demand. However, the mechanical properties of glass-based ceramics, such as fracture toughness, low tensile strength, and wear resistance, have limited their clinical use⁵. The introduction of zirconia-supported ceramic has generated considerable interest in restorative dentistry because of its high esthetics, biocompatibility, chemical, and mechanical durability⁶.

One main drawback of zirconia-based ceramics is their high opacity, which limited their use in the esthetic zone. Porcelain veneering of a zirconia core material has resulted in more esthetically accepted restorations⁷⁻⁹. However, the chipping of veneered porcelain is the primary clinical weakness of dental bilayered ceramic structures, with a rate of (6% and 15%) over 3 to 5 years¹⁰⁻¹³. Other failures are often multifactorial and can be associated with improper thermal-related interfacial residual stresses, substructural design, and non-standardized processing techniques¹⁴. The main triggers for unsuitable residual stresses during fabricating the bilayered ceramic restorations are the different ceramic cooling rate, resulting from the mismatch in coefficients of thermal expansion of zirconia core and the veneering

porcelain¹⁵⁻¹⁷. This opened the door for the introduction of the full contoured zirconia restoration (monolithic zirconia), which is manufactured by the CAD/CAM technology.

The main advantage of the monolithic zirconia is the elimination of porcelain chipping from the bilayered restorations¹⁸⁻²⁰. However, this material's main shortcoming was the esthetic performance due to the lack of achieving natural transparency^{18,21}. Several studies attempted to improve the opaque zirconia's esthetic appearance by introducing the full contour translucent zirconia, which was claimed that the material is combining the translucent esthetic properties with sufficient fracture resistance²².

Several advantages made the translucent zirconia the material of choice over the other dental restorations; its relative translucency has been considered one of the main advantages, which categorized it as an esthetic material that indicates its use for anterior fixed prostheses²³. Other advantages include the mechanical strength, where the studies showed that the fracture strength of the translucent zirconia is greater than that of lithium disilicate and multilayered restoration²⁴⁻²⁶, however, the strength of translucent zirconia is brand dependent²⁷. The tooth preparation for monolithic crowns is relatively minimal and saves more tooth structures compared to other ceramic materials. Nakamura *et al.* indicated that translucent zirconia in 0.5 mm thickness had a higher fracture strength compared to lithium disilicate with 1.5 mm occlusal thickness²⁸.

However, there are two main drawbacks of the translucent zirconia, the first one is its susceptibility to low-temperature degradation (LTD), in which the spontaneous phase transformation from tetragonal to monoclinic is higher compared to traditional veneered zirconia. The veneering porcelain in the multilayered

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zirconia restorations protects the zirconia core from direct exposure to the oral environment and reduce such degradation. The absence of the veneering porcelain in the translucent zirconia crowns makes it more susceptible to LTD²⁹⁻³¹⁾. The second drawback of translucent zirconia is its suboptimal esthetic properties; the translucent zirconia is still less translucent than lithium disilicate according to the translucency parameter (TP). The TP is defined as the color difference of a material of a given thickness over white and black backgrounds³²⁾. Yu *et al.* in 2009 reported that the TP values of 1 mm thickness of human dentin and enamel is 16.4 and 18.7, respectively³³⁾. The TP of translucent zirconia is ranging between 11.2 and 15.3, which is significantly less translucent compared to enamel and to lithium disilicate, which have a TP value of 16.89²⁶⁾.

The effect of porcelain veneering of translucent zirconia crowns' mechanical behavior has not been investigated in the literature previously. Therefore, this study aimed to assess the effect of different crown designs on the fracture resistance of thermally-fatigued veneered translucent zirconia crowns compared to the full-contoured monolithic translucent zirconia crowns.

MATERIALS AND METHODS

Dies preparation

Hard thermo-setting plastic tooth models of tooth #46 (Frasaco, Tettang, Germany) was scanned using a 3D scanner (Ceramill map 400+, Amann Girrbach, Koblach, Austria). Then prepared with 10–20 degree total occlusal convergence, 1.0 mm uniform reduction of the buccal, lingual, and occlusal surfaces, and the proximal surfaces were prepared to remove the undercuts with a minimum reduction of 1.0 mm with round-end tapered diamond bur (8868.314.012/868.314.012 burs; Komet Dental, Lemgo, Germany). The plastic tooth was duplicated using a polyurethane-based model stump material (alpha die MF Ivory precision die material, Schütz Dental, Rosbach, Germany) to a ninety duplicated dies.

Crown fabrication

A total of 90 standardized crowns with different designs were fabricated and divided into six groups ($n=15$); The tested crown designs are illustrated in Fig. 1.

- Group 1: 1 mm-thick fully contoured monolithic translucent zirconia crown (FMC).
- Group 2: Fully veneered translucent zirconia core with 0.5 mm porcelain veneer (FVC).
- Group 3: Partially veneered translucent zirconia crown with a 0.5 mm buccal veneer (PVL).
- Group 4: Partially veneered translucent zirconia crown with a 0.5 mm buccal veneer with 1 mm buccal collar height (PVC_o).
- Group 5: Partially veneered translucent zirconia crown with 0.5 mm buccal veneer supported by wave design (PVW).
- Group 6: Partially veneered translucent zirconia crown with 0.5 mm buccal veneer supported by occlusal cap design (PVC_a).

Fig. 1 A 3D illustration of the experimental crown design groups.

A) group 1: fully contoured monolithic translucent zirconia crown design; B) group 2: fully veneered translucent zirconia core with 0.5 mm porcelain veneer design; C) group 3: partially veneered translucent zirconia crown with 0.5 mm buccal veneer design; D) group 4: partially veneered translucent zirconia crown with 0.5 mm buccal veneer with 1 mm buccal collar height design; E) group 5: partially veneered translucent zirconia crown with 0.5 mm buccal veneer supported by wave design; F) group 6: partially veneered translucent zirconia crown with 0.5 mm buccal veneer supported by occlusal cap design

The designing of the respective crowns was performed using CAD software (Ceramill Mind software, Amann Girrbach) according to our study design. All the crowns were milled from pre-shaded translucent zirconia blocks (Ceramill, Zolid HT+ pre-shaded, Amann Girrbach), using a 5-axis milling machine (Ceramill Motion 2, Amann Girrbach). The milled crowns were sintered at 1,450°C for 9.5 h using a sintering furnace (Ceramill therm 3, Amann Girrbach).

The veneering surface of the crown copings with reduced anatomical shape (Groups 2–6) were sandblasted with 50 μ aluminum oxide particles (Korox-50-Crndm-Blast-Mat, Bremen, Germany) under a pressure of 30 psi for 15 s at a direction perpendicular to the veneering surface, and steam cleaned for 5 s before applying the porcelain veneer layer. Feldspathic porcelain (Soprano 10, Cendres+Métaux Medtech, Biel/Bienne, Switzerland) was applied in multiple layers (Modifier, Dentin A2, Enamel A2, glaze), and the crowns were fired in a calibrated furnace according to the manufacture recommendation. The crown's thickness was measured at five standardized points, using a dial gauge (Calipretto CR, Renfert, Hilzingen, Germany) to verify the thickness.

Cementation

The surface of the dies were sandblasted with 50 μ aluminium oxide particles and cleaned in an ultrasonic

water bath. Each crown was bonded onto its respective die using a self-adhesive resin cement (RelyX Unicem 2 Automix, 3M ESPE, Seefeld, Germany). A standardized static load (20 N) was applied on the occlusal surface of each crown for 30 s, and then the excess cement was removed from the margins using a micro-brush. All the specimens were light-cured for 20 s from the buccal and lingual aspects using an LED light-curing unit (Elipar DeepCure, 3M ESPE) with an output of 1,470 mW/cm². The intensity was verified in every 10 samples using a digital radiometer (Cure Rite, Dentsply, Milford, DE, USA) to ensure uniform curing. Specimens were stored in a moist environment for 24 h at 37°C in an incubator before the mechanical testing (Incubator I, Memmert, Schwabach, Germany).

Thermal aging

The specimens were simultaneously thermo-cycled for 5,000 cycles between two temperature extremes of 5°C and 55°C in distilled water (dwell time: 30 s, pause time: 13 s) and performed in a computerized thermocycling unit (SD Mechatronik, Feldkirchen Westerham, Germany).

Fracture resistance testing

All specimens were loaded to fracture in a universal testing machine (Universal testing machine, M350-5CT, Testometric, Rochdale, UK). A custom-made semi-spherical stainless-steel indenter ($\varnothing=4$ mm) was used, and each sample was positioned at a 45° to the indenter's long axis. The indenter was placed against the lingual inclination of the buccal cusp on a standardized occlusal point 2 mm away from the cusp tip. A compressive load was applied vertically at a crosshead speed of 1.0 mm/min until fracture. The load at failure was recorded in Newtons (N).

Failure mode analysis

The fractured surfaces of the crowns were assessed by two examiners. A gross visual inspection under a stereomicroscope (Leica EZ4, Leica, Wetzlar, Germany) with 30× magnification were performed to classify the fracture mode into one of three failure modes; 1) adhesive

failure: denoting fracture in the interface between the ceramic veneer and the zirconia core, 2) cohesive failure: denoting fracture within the ceramic veneer, i.e., chipping, or 3) complete failure: denoting fracture through both the veneer layer and the zirconia core.

Statistical analysis

The fracture resistance data were tested using a Shapiro-Wilk test for normality and were further analyzed by one-way analysis of variance (ANOVA) and Tukey's *post-hoc* multiple comparison tests for pairwise comparisons at $p<0.05$, to test the significant differences in fracture resistance between the tested groups. The differences in mode of failure between and within the six groups was revealed using Chi-square test. The inter-examiner agreement was assessed using Kappa statistics. All the statistical analysis tests were performed using SPSS software version 23.0 (SPSS/IBM, Armonk, NY, USA).

RESULTS

The mean fracture of the six tested groups, measured in N, are listed in Table 1 and presented graphically in Fig. 2. The highest mean fracture resistance was recorded for the (FMC) group, and the lowest fracture resistance was in (FVC) group. The other four groups were ranking between the mentioned groups from highest to the lowest as follow (PVCa), (PVL), (PVCo), and (PVW). One-way ANOVA analysis fracture resistance showed statistically significant differences between the tested experimental groups ($p=0.038$). *Post-hoc* Tukey HSD test revealed a significant difference ($p<0.05$) in fracture resistance of FMC compared to FVC ($p=0.025$). However, the mean fracture resistance of FMC was not significantly different ($p>0.05$) compared to PVL, PVCo, and PVW.

None of the tested groups demonstrated adhesive failure mode. All crowns in the FMC, PVL and PVCa groups (100%) and all but one of the crowns in both PVW and PVCo (93.3%) showed complete fracture (Fig. 3a) with significant differences ($p=0.025$) in the fracture mode compared to the FVC where it showed (73.3%) complete fracture and (26.7%) cohesive failure (Fig. 3b)

Table 1 Mean fracture resistance (N), standard deviations, significance and Mode of Failure (%) of the tested experimental groups

	Fracture resistance	Mode of failure (%)		
	Mean±SD	Complete	Cohesive	Adhesive
(FMC)	1,140±198 ^a	100	—	—
(FVC)	775±212 ^b	73.3	26.7	—
(PVL)	954±242 ^{ab}	100	—	—
(PVCo)	932±249 ^{ab}	93.3	6.7	—
(PVW)	859±114 ^{ab}	93.3	6.7	—
(PVCa)	975±312 ^{ab}	100	—	—

Note: Values with the same superscript letters were not statistically different at ($p>0.05$).

Table 2 In between groups analysis using Chi-square test

	Chi-square tests		
	Value	df	Asymptotic significance (2-sided)
Pearson chi-square	12.857*	5	0.025
Likelihood ratio	11.994	5	0.035
Linear-by-linear association	7.326	1	0.007
Number of valid cases	90	—	—

Fig. 2 Box plot representing the median, minimum, maximum and interquartile range of all the groups.

FMC; fully contoured monolithic translucent zirconia crown, FVC; fully veneered translucent zirconia core with 0.5 mm porcelain veneer, PVL; partially veneered translucent zirconia crown with a 0.5 mm buccal veneer, PVCo; partially veneered translucent zirconia crown with a 0.5 mm buccal veneer with 1 mm buccal collar height, PVW; partially veneered translucent zirconia crown with 0.5 mm buccal veneer supported by wave design, PVCa; partially veneered translucent zirconia crown with 0.5 mm buccal veneer supported by occlusal cap design

Fig. 3 Representative stereomicroscope images showing a) complete fracture of the crown over the resin die (D), involving porcelain veneer (P), zirconia core (Zr) and cement layer (C), and b) cohesive fracture within the porcelain veneer (P).

using Chi-square statistical test (Table 2). Results of Kappa statistics revealed a very high agreement ($\kappa=1.00$) between both examiners for the type of failure.

DISCUSSION

The one-way ANOVA test showed a significant effect of the crown design among the tested groups ($p=0.038$), which contraindicates the null hypothesis, and this is why the null hypothesis was rejected.

The results of this study showed that the mean fracture resistance of the fully contoured monolithic translucent zirconia crown FMC exhibited the highest fracture resistance compared to all the other designs. This finding is in agreement with the results of Bakitian *et al.*³⁴ who found that the monolithic translucent zirconia crowns had the highest fracture resistance compared to the other tested groups, and the strength of the translucent zirconia can explain this over the glassy lithium disilicate²⁴⁻²⁶.

The fracture resistance results can be explained according to each suggested crown design. In PVCo design, the cervical collar may have acted as a ferrule, which may have reduced the stresses at the cervical margin, thus increasing the fracture resistance³⁵. For the PVCo, PVW, and PVL designs, most of the occlusal surface is supported by the translucent zirconia. Furthermore, the waves support in the PVW may act to eliminate shear forces from growing on the buccal veneer- zirconia interface. Bakitian *et al.* tested similar designs to PVCo, PVW, and they reported that the fracture resistance of these groups is approximately close to that with the full monolithic design. Moreover, they reported that the 0.5 mm partially labial veneer for a full monolithic translucent zirconia crown was inferior to the other tested designs in terms of fracture resistance. The authors contributed their findings to the thickness of the veneered layer, as the thicker the porcelain veneer, the higher probability of flaws within the material, and accordingly, the lower fracture strength. Which will results in, and they suggested keeping the labial veneer thickness to 0.3 mm in such a design. However, in their study, the fully veneered zirconia crowns were not tested to confirm their conclusion³⁴.

In contrast, the results of the current study showed that mean fracture resistance of PVL was statistically similar to that of FMC. These results can be attributed to the testing setup, where most of the load on the tested samples was mimicking the clinical scenario, in which the palatal cusp of the upper first molar is engaging the

lingual slope of the buccal cusp of the lower first molar. The buccal cusp was supported by translucent zirconia in all the tested designs of the present study.

In the current study, the lowest mean of the fracture resistance in the tested designs was recorded for FVC, which was reported to exhibit a higher chance of porcelain chipping by several studies¹⁰⁻¹³⁾ and a lower fracture resistance when compared to the fully monolithic zirconia restorations^{36,37)}, in which monolithic crowns displayed a higher resistance to fracture compared to bilayered restoration. Our results showed that the overall mode of failure in the six groups was a cohesive failure (6.7%) as compared to complete failure (93.3). The Chi-square statistics revealed a significance between the tested groups ($p=0.025$), which was present between the FVC group and the other tested groups (Table 1).

The present study showed that FMC, PVCa, and PVL showed only a complete failure mode compared to PVW and PVCo where both had presented with (93.3%) complete failure and (6.7%) cohesive failure. Meanwhile, FVC showed (73.3%) complete failure and (26.7%) cohesive failure. These results can be attributed to the chipping tendency of the porcelain veneer, which is the main cause of failure of the bilayered zirconia restoration in both clinical and laboratory studies¹²⁾.

The majority of the mode of failure in the present study were a complete crown fracture, and that can be explained by the impact of the load on the tested designs placed over the translucent zirconia part, and which eliminate the chance of the tensile stresses to build up in the veneer layer. Thus, it resulted in a full load of impact over the zirconia material, where it tested the zirconia structure rather than the bilayered structure.

Some of the fully veneered crown design showed a cohesive failure in the veneered layer in which a thin layer of the porcelain is still attached to the core, and that can be explained by the difference between the veneered porcelain and the zirconia core in terms of the fracture resistance since it is weaker compared to the core and thus making it more prone to fail at lower loads³⁸⁾. Other cause of the cohesive failure in the veneer layer can be the high residual stresses in the porcelain layer, and it might be related to the low thermal diffusivity of the zirconia, which can affect the cooling of the veneered layer; that difference in the cooling rate can lead to more residual stresses in the veneered layer³⁹⁾.

Bakitian *et al.* investigated the mode of failure in several translucent crown designs similar to the present study designs FMC, PVW, PVL, and PVCa. They also added 0.3 mm partially labial veneer for a full monolithic translucent zirconia crown (SM0.3), and they found that both (FMC) and (SM0.3) showed only a complete failure compared to PVCa, the latter showed (95%) complete failure and (5%) cohesive failure. However, both PVW and PVL revealed a significant difference of (70% and 55%, respectively) of cohesive failure, and (30% and 45% respectively) of complete failure³⁴⁾.

Furthermore, the present *in vitro* fracture resistance testing, using a single compressive unidirectional loading, provides only limited understanding into

clinically relevant mechanisms of crown's damage under forces with different directions and cyclic loading and thermal fatigue. It may be anticipated that tensile stresses can induce numerous secondary fractures and generate multiple cracks and different modes of failure⁴⁰⁾. Thus, further investigation of the proposed crown designs is required under more clinically relevant testing conditions.

CONCLUSIONS

Within the limitations of the present study, it can be concluded that;

1. The introduced partially veneered translucent zirconia crown designs in the present study showed a comparable fracture resistance to that of the monolithic translucent zirconia crown.
2. The fracture resistance of all the tested crown designs was comparable to that of the full contoured monolithic translucent zirconia crown except for the full veneered design.
3. The mode of failure of the partially veneered crowns was similar to that of the fully contoured design with minimal chipping of the porcelain veneer. Moreover, FVC showed a higher chance of chipping compared to the other designs.

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