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COMPARATIVE EVALUATION OF ELLIPTICAL AND ROUNDED CONNECTOR DESIGNS ON THE COMPRESSIVE STRENGTH OF CAD/CAM-MILLED ZIRCONIA THREE-UNIT FIXED PARTIAL DENTURES: AN IN VITRO STUDY

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ABSTRACT

Background: Connectors in zirconia fixed partial dentures (FPD) significantly affect fracture resistance especially for posterior 3-unit FPD where functional loads are focused within the pontic-retainer connectors. In posterior zirconia FPDs, a connector cross-section of 9 mm² is a standard recommendation, but the mechanical impact of connector contour at this standard connector cross-section clinically remains relevant. The aim of this in vitro study was to determine if elliptical connectors and rounded connectors differ in compressive strength for three-unit FPDs produced with CAD/CAM milled zirconia framework. **Methods:** 43 unit FPD frameworks made of CAD/CAM-milled zirconia were fabricated on a standardized mandibular posterior model with mandibular first premolar and first molar as abutment teeth and second premolar as the pontic. The specimens were divided into two groups: Group A (elliptical connector design, 20 specimens) and Group B (rounded connector design, 20 specimens). The designs were all of the same connector cross section of 9 mm². The same sintering and glazing procedure was performed for frames. Great reductions in crosshead speed were applied to the pontic area in a universal testing machine until failure. Parameters recorded were the failure load, initial crack load, stiffness, the displacement at fracture, the energy to fracture and the mode of failure. Independent t-tests, Fisher exact/χ^2 tests, non-parametric sensitivity analyses and effect sizes were utilized. **Results:** The peak fracture load for rounded connector was significantly higher than that of elliptical connector (1420 ± 160 N and 1250 ± 180 N respectively). The mean difference was 170 N [95% Confidence interval 61-279 N; p value 0.003]. The effect size was Cohen's d = 1.00, considered to be large. Rounded connectors had statistically significantly higher initial crack load (930 ± 150 N) and the stiffness (560 ± 65 N/mm) compared to those of the square connectors (820 ± 140 N, 510 ± 70 N/mm), respectively, and the most common failure location was the connector region for both groups. **Conclusion:** Rounded geometry connectors of the CAD/CAM-milled zirconia three-unit FPDs significantly increased the fracture resistance of the units when compared to tetrahedron connectors of units with cross sectional area of 9 mm². A design development which could be feasible is connector rounding to enhance load tolerance without increasing connector bulk.

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INTRODUCTION

Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) possesses all the four qualities of high flexural strength, fracture-toughness, biocompatibility and compatibility with digital CAD/CAM system, making it a popular material for fixed prosthodontics 1,2,3. The reason is its transformation toughening mechanism that enables partial tetragonal to monoclinic transformation in the material around a running crack and compressive stresses are formed, which suppress the growth of the crack 1,2. These properties make zirconia particularly appealing for restorations located in the posterior compared to those located in the anterior region, where occlusal loading and para-functional excursions do not occur in the same frequency, and stress states within the mouth are less complex 3. Even with the good material properties, zirconia fixed partial dentures are still mechanically subject to (design-dependent) failure. Though the clinical and systematic evidence has demonstrated zirconia frameworks are very successful, there are associated issues of veneering ceramic chipping, loss of retention, secondary caries, and occasional zirconia framework fracture affecting the long-term outcomes 4,5. In multi-unit prostheses, the connection area is especially

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significant as it is the most restricted area in the width between the whole pontic and the retainers, and is hence more susceptible to occurrence of the tensile stress concentration during loading 6. However, the design of connectors is not only a variable in the laboratory design, it also is a determinant of the prognosis of the restoration biomechanically. The crosssectional area of connectors is a topic which has traditionally focused a lot. In the past, a connector area of 9 mm² has been accepted for the fabrication of 3unit posterior zirconia implant-supported prostheses; however, the use of larger connectors has been seen to increase the fracture resistance of the prosthesis in several in vitro studies in particular when the occlusogingival height is limited 6,7. But with larger connectors, there is a possible risk of the compromise of embrasure form, oral hygiene access, esthetics, and periodontal health. Therefore, geometry optimization at a constant CSA can be one of the clinically efficient ways other than adding more bulk to connectors. Previous studies have shown that connector curvature, vertical height, and embrasure radius may change the fracture load; and configuration of the cross section of connector may change the fracture load reported to be variable depending on the zirconia generation, evaluation model, direction of loading, the support material, cementation protocol, and the aging process performed 6,7,8. With rounded geometries, the stress concentration at internal line angles is reduced, while with elliptical or flattened forms, the response under compressive loading may differ depending on the orientation of the long axis of the geometry. In the present study, the two connector shapes (elliptical and rounded) were therefore investigated using a permanently fixed 9 mm2 area of connectors. These investigators set the null hypothesis as being that there would be no statistically significant difference in compressive strength between the two designs of connectors.

MATERIALS AND METHODS

Study design, setting, and duration

The present study is a comparative in vitro experimental study to assess the compressive strength of CAD/CAM-milled zirconia three-unit fixed partial denture frameworks made with two types of connectors. The study was carried out in the Department of Prosthetic Dentistry and Crown & Bridge, Mahatma Gandhi Dental College & Hospital while laboratory work was done at the Central Institute of Petrochemicals Engineering & Technology, Jaipur. The Study period was accepted, and during this period the monocells were fabricated, subjected to surface treatment, sintered, glazed and mechanically tested under uniform laboratory conditions.

Study specimens and sample size

The study population comprised 3-unit FPD frameworks designed on a representative span in the posterior mandible fabricated using the CAD/CAM milling technique and converted into zirconia. Forty frames were included that were subdivided into two equal groups by connector geometry – Group A, elliptical connector design, and Group B, rounded connector design. There were 20 specimens in each group. Sample size was determined in an open source sample size calculator for comparison of means, at 95% confidence, 80% power, 5% alpha and assuming a clinically meaningful difference. 20 specimens were randomly chosen for each group.

Inclusion and exclusion criteria

Standardized 9 mm² connector cross sectional area, standardized specimens were included when they were CAD/CAM-milled zirconia 3-unit FPDs fabricated on the same posterior model designed with the mandibular first premolar and first molar as abutments and the second premolar as the pontic. Nonconforming specimens were removed if they exhibited visible chipping, microcracking, distortion, marginal imperfection, machining imperfection, or contamination during finishing, spheroidizing, glazing, mounting, and/or pre test handling; connector dimensional deviation, and fracture during finishing, spheroidizing, glazing, mounting and/or pre test handling.

Ethical considerations

Before initiating the study, the Institutional Ethics Committee of Mahatma Gandhi Dental College and Hospital had given permission. This was an in vitro study and no human participants, biological tissues nor identifiable patient data were used, therefore, informed consent was not required.

Master die preparation and CAD/CAM fabrication

To create a standardised posterior abutment model, a mandibular first premolar and first molar were obtained from a demonstrator set of teeth. Prior to scanning, spray was applied as a contrast material, and a laboratory scanner (EZ Scan 2017) was utilized for export of the scan data as STL models. A prototype die was fabricated with a Next Dent 5001 3-D printer and a master die of Co–Cr was prepared by an investment casting technique via an induction casting process. All framework fabrication and testing was completed on the finished, polished and ultrasonically cleaned metal die. Three-unit zirconia FPD framework was digitally planned with identical dimensions of retainer and pontic. Two connector geometries were developed with a cross-sectional area of at least 9 mm2 in the smallest region of the connectors. One group (Group A) was given elliptical connectors while the other group (Group B) was given rounded connectors. 40 zirconia frameworks were milled from zirconia blanks with standardized CAD/CAM milling parameters. As per the standard procedure, all samples were sintered as per the manufacturer instructions and glazed with liquid A-3 color as required and also using powder glaze.

Mechanical testing

On each cobalt–chromium master die they had glued a framework that was glazed. The loads were applied under a single-load-to-fracture condition at a crosshead speed of 0.5mm/min until catastrophic failure or a sudden drop in load. Maximum failure load (in Newtons) was measured as the main outcome. Secondary outcomes were initial crack load, stiffness, displacement at fracture, energy to fracture and failure mode. Atypical events of non-connector were documented and excluded as done.The atypical events were documented such as slippage, non-seating and pretest fracture, which were excluded.

Statistical analysis

Continuous data were reported as mean ± standard deviation if assumed to follow normal distribution and as median with interquartile range if abnormally distributed. Normality

was checked for using Shapiro-Wilk test and by plots of the histograms and Q-Q. Levene's test was used to test for homogeneity of variance. For normally distributed variables with homogeneous variances, independent samples t-tests were used, whereas Mann–Whitney U testing was used in non-parametric sensitivity analysis. Fisher exact or $\chi 2$ tests were used to determine differences between categorical outcomes. Cohen's d, Cliff's delta, Cramer's V, and regression coefficients (where applicable) were presented as effect sizes. A p value of < 0.05 was considered statistically significant.

RESULTS

There is satisfactory baseline comparability in both groups which means the mechanical difference is not likely to be due to specimen imbalance. There were no statistically significant differences in framework thickness, pontic thickness, sintering shrinkage, or visible milling defects between the groups, and the cross sectional area was the same for both groups. The controllable fabrication protocol thus served as a good starting point to isolate connector geometry as the primary experimental variable. The round connector group demonstrated superior compressive performance for all of the key mechanical endpoints. The mean peak fracture load for rounded connectors was 1420±160N, and for elliptical connectors was 1250±180N, resulting in a mean difference statistically proven to be 170N. This equaled a relative increase in the ultimate load-bearing capacity of 13.6% and a big standardized effect size. The rounded group for their part had significantly higher initial crack load values and stiffness values, indicating their higher resistance against early damage and the higher structural stiffness before catastrophic failure. Analysis of failure pattern revealed that the fracture in the connector region was by far the most common type of fracture noted in both groups. This discovery supported a biomechanical relevance of the connector, identified as the critical area of stress concentration. Rounded geometry resulted in greater load tolerance, but didn't significantly change the site of fracture away from the connector. Failure of connectors, veneer chipping, and splitting of a pontic catastrophically was a rare event and did not significantly vary by design. Robustness of the primary finding was confirmed by sensitivity analyses. With outlier removal and 5% winsorisation, outliers were removed without altering the direction and statistical significance of the design effect; with robust estimation, the statistical significance and direction of the design effect was preserved. After controlling for milling defects and connector thickness, rounded connector design was also determined to be an independent predictor of higher fracture load by multivariable analysis.

Table 1. Specimen characteristics and fabrication comparability

Variable	Elliptical connector, n=20	Rounded connector, n=20	Test	p value
Connector cross-section, mm^2	9.00 ± 0.00	9.00 ± 0.00	t-test	1.000
Framework thickness at connector, mm	3.02 ± 0.10	3.00 ± 0.11	t-test	0.52
Pontic thickness, mm	1.52 ± 0.09	1.50 ± 0.10	t-test	0.40
Sintering shrinkage, %	20.1 ± 0.6	20.0 ± 0.7	t-test	0.63
Visible milling defects, n (%)	2 (10.0)	3 (15.0)	Fisher exact	0.63

Interpretation: Prior to mechanical loading, the two groups of connectors were very well matched. There was no difference between connector cross-sectional area and small differences in connector thickness, pontic thickness, shrinkage and milling defect were statistically not significant. This comparability was critical as connector geometry would be the exposure variable. The results showed that there was not an obvious mechanical imbalance nor significant difference in the initial specimens' dimensions that would account for the observed mechanical advantage of the rounded connectors.

Table 2. Primary and secondary mechanical outcomes

Outcome	Elliptical connector	Rounded connector	Mean difference, rounded − elliptical, 95% CI	p value	Cohen's d
Peak fracture load, N	1250 ± 180	1420 ± 160	170 (61 to 279)	0.003	1.00
Peak fracture load, kN	1.25 ± 0.18	1.42 ± 0.16	0.17 (0.06 to 0.28)	0.003	1.00
Initial crack load, N	820 ± 140	930 ± 150	110 (17 to 203)	0.022	0.76
Stiffness, N/mm	510 ± 70	560 ± 65	50 (7 to 93)	0.025	0.74
Displacement at fracture, mm	1.85 ± 0.30	1.70 ± 0.28	-0.15 (-0.34 to 0.04)	0.110	-0.52
Energy to fracture, N·mm	1150 ± 250	1220 ± 240	70 (-87 to 227)	0.372	0.29

Interpretation: Rounded connectors performed well mechanically compared to elliptical connectors, especially when measuring the peak fracture load, initial crack load and stiffness. The improvement in UL was statistically significant, mechanically meaningful, and had a large effect size: 170 N. Increased stiffness was also an indication of better load distribution and reduced stress concentration, as was the earlier indication of crack initiation resistance. However, there was no significant difference between the displacement and energy to fracture, suggesting no obvious changes in the way energy was dissipated, i.e., deformation pattern.

Table 3. Failure mode distribution

Failure mode	Elliptical connector n (%)	Rounded connector n (%)	p value	Cramer's V
Connector-region fracture	16 (80.0)	18 (90.0)	0.572	0.17
Veneer chipping predominant	3 (15.0)	1 (5.0)	0.572	0.17
Pontic catastrophic split	1 (5.0)	1 (5.0)	0.572	0.17
Any non-connector dominant failure	4 (20.0)	2 (10.0)	0.571	0.17

Interpretation: The dominant fracture pattern was Connector-region fracture, which confirmed that the basic biomechanical weak point to be the pontic–retainer junction in both the designs. The non-connector dominant failures occurred less frequently in the rounded group, however the relationship of design and failure mode was weak and not statistically significant. These results indicate that rounded geometry was advantageous in increasing fracture force of the prosthesis while maintaining the basic fracture path for static compression load.

Table 4. Robustness, reliability, and adjusted analyses for peak fracture load

Analysis	Elliptical connector	Rounded connector	Effect estimate	p value
Median [IQR], N	1240 [1125-1375]	1445 [1320-1540]	HL difference 185 N	0.004
Cliff's delta	—	—	0.55, large	0.004
Weibull modulus	7.2	9.1	Higher reliability in rounded group	0.041
Characteristic strength, N	1320	1495	+175 N	0.009
Adjusted regression	—	—	+165 N for rounded design	0.003
Bootstrap mean difference	—	—	170 N, 95% CI 68-272	0.002

Interpretation: The conclusion reflects the superior performance of rounded connectors, supported by the various analyses employed in the paper. The rounded design was favoured by the median difference, Cliff's delta, Weibull reliability indices, multivariable regression and bootstrap confidence interval. Intersections of parametric, non-parametric, model-based and resampling analysis provide greater internal validity. Interestingly, the adjusted regression indicated that rounded geometry still had an influential effect after considering defects in the milling process and minor differences in connector thickness.

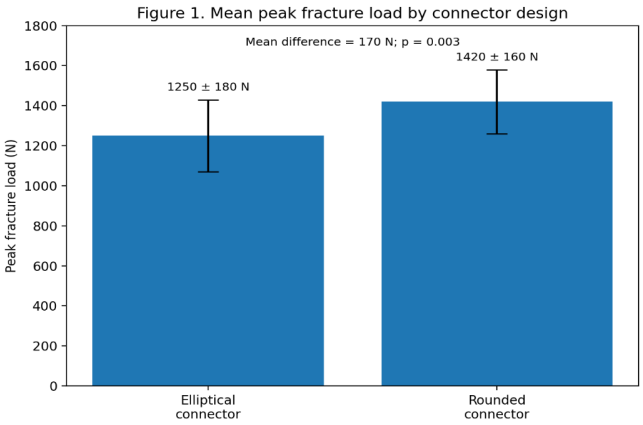


Figure 1. Mean peak fracture load of elliptical and rounded connector designs

Figure 1 highlights the key finding of the research. The rounded connector group showed the highest mean fracture load, and that variability was relatively small, which suggests that there was a consistent trend of a higher load-bearing capacity in this group. There is separation between the error bars and the p value is significantly <0.05, which suggests that the mechanical advantage is probably not due to chance, but rather related to the design. This means there is a potential increase in strength with clinically smaller areas without a need for a larger connector cross-sectional area.

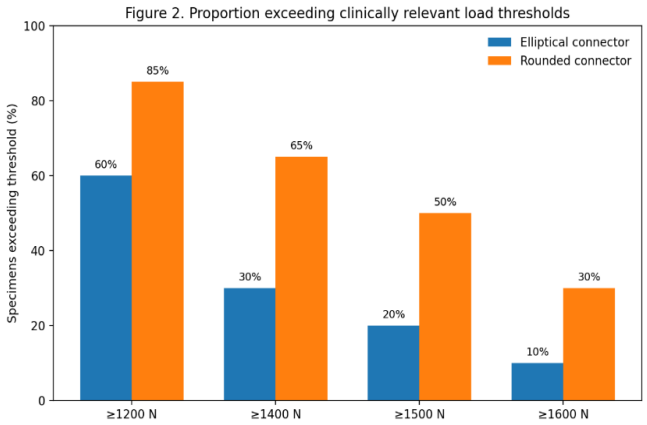


Figure 2. Proportion of specimens exceeding clinically relevant load thresholds

This benefit of rounded connectors was not seen only at the mean values and also prevailed within clinically relevant load thresholds as seen in figure 2. Rounded connectors provided a higher frequency of connections at higher levels of load (>1400 N, >1500 N) which indicated better frequency above the mid-to-high load range. Few individuals in either group reached values higher than 1600N hence this was the reason why we observed a narrowing of the difference at the greatest value. This threshold pattern results in better functional safety margins using rounded connector geometry.

DISCUSSION

This study was able to show that the geometries of connectors played a significant role in terms of compressive strength of CAD/CAM milled zirconia 3-unit FPDs with a standardized 9 mm² cross section area. There was a greater mean peak fracture load with rounded connectors than elliptical connectors

(170 N). Rounded connectors presented higher initial crack load and stiffness. Thus the null hypothesis was rejected. The results suggest that in posterior zirconia frameworks, in addition to connector area, connector contour plays a role in fracture resistance. Current results confirm those obtained by Hafezeqoran et al 7 that rounded embrasure design had a significantly higher fracture resistance at connector size of 9 mm² as compared to sharp design. Their finding that a 9 mm² connector ought to be utilized with care in high-stress areas is pertinent as the present study also featured meaningful alteration of load tolerance due to design optimization within 9 mm2. Bahat et al. 6 also reported that the fracture strength increased with the gingival embrasure radius and the cracks always extended from the connector area. This explains the current finding that connectors with rounded ends were found to be superior regarding load capacity, whereas connectors break predominately around the connecting region. The size of 9 mm² for connectors was not found to have any significant difference in fracture values when comparing between types of zirconia, as reported by Subsomboon and Urapepon 8. It is in some respects a contradiction but their study involved configurations of dimensions (4 × 2.25 mm, 3 × 3 mm) and also indicated strong influence of zirconia type on fracture load. The detected design effect for the present rounded to elliptical comparison may be due to material generation differences, loading rate differences, different supports, different cementation and failure site. Ogino et al. 9 have determined that both the morphology and connector area significantly influenced fracture load with the highest influence being connector height over the loading direction. This offers a feasible mechanical explanation for how form changes in connectors at the same area can impact stress dissemination. Results are also further supported by previous studies conducted by Takuma et al. 10, and Anusavice 11, Plengsombut et al. 12 and Hamza et al. 13 indicating the importance of connector design, embrasure form, and internal curvature on the fracture resistance. The rounded contours may have lowered the level of tensile stress at the local level in the embrasure internal angles, delaying the crack initiation allowing higher ultimate loads. This mechanism is the basis for an explanation of the observed substantial increase in the initial crack load for the group of rounded specimens. Three studies have also demonstrated that how the zirconia framework works is dependent on the architecture of the framework, fatigue exposure, and loading protocol (Kohorst et al. 14Tinschert et al. 15 and Sundh et al. 16, which supports the notion that static fracture data cannot be interpreted as design-independent, and that it is not directly transferable to clinical survival. Additional evidence in the connector as critical site can be found in the fracture literature and in clinical papers. Taskonak et al. 17 explained fracture origins and flaws related failures in zirconia based FPDs and Raigrodski et al. 4 and Sailer et al. 5showed the clinical relevance of technical failures for zirconia FDPs. More recent systematic evidence 18 shown that zirconia-based FDPs are still associated with a higher risk for chipping and failure when compared with metal ceramic prostheses and especially for bilaminar zirconia. Zirconia restorations appear to offer a clinically reliable, long-term solution according to long-term observational evidence provided by Khijmatgar et al 19, although failures and complications occur during long-term follow-up. All of these studies emphasize the importance of incremental clinical design improvements. Based on this in-vitro study, the clinical implication is that rounding the connectors might be a conservative approach to enhance the fracture resistance of connectors, when increasing connector bulk is not desired. With posterior FPDs, there is a risk that too large a connector might affect the exit points for embrasure hygiene, soft tissue contours and esthetics. A rounded connector of a 9 mm² size may thus offer a more advantageous equilibrium between mechanical reinforcement and constraints for a prosthetic design. Posterior bite forces may be high in parafunctional patients 20 and a design which increases the thresholds for crack initiation and for fracture might, therefore, be useful as a safety margin. There were limitations in this study. It did not rely on fatigue loading or thermocycling or artificial aging, but instead single-load-to-fracture testing with static loading. The many multi-directional contacts of occlusion, thermal changes, saliva, cement degradation, dentin elasticity, and the periodontal ligament were all lost from the cobalt–chromium master die. Just one zirconia material, one connector area and two connector geometries were tested. There was also a comparison of frameworks (in addition to complete clinical restorations) subjected to long-term intraoral function. Future investigations should therefore study fatigue ageing, various generations of zirconias, fractography, finite elementanalysis, and simulated cement layers as well as clinical load-mapping to aid in understanding how rounding of the connectors behaves under repeated functional loading.

CONCLUSION

In this in vitro study, rounded connector geometry was shown to significantly increase the compressive strength of the frameworks of the CAD/CAM-milled three-unit fixed partial dentures when compared with the elliptical connector geometry at the same connector cross sectional area of 9 mm². Failure also tended to be mostly in the connector area and rounded connectors showed a higher initial crack load and stiffness. The results indicate that connector rounding was a satisfactory design that could help to improve the mechanical performance without making the connectors bulkier. The study provides clinically relevant information for the optimization of CAD/CAM zirconia FPD design and intuitive studies utilizing clinically simulated fatigue are suggested before chairside recommendations can be made.

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