Original Article

Effect of Framework Design on Fracture Resistance in Zirconia 4-unit All-ceramic Fixed Partial Dentures

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Abstract

The purpose of this study was to conduct static load-bearing tests on 4-unit YTZP all-ceramic fixed partial denture (FPD) frameworks with different cross-sectional areas and forms to evaluate the influence of connector design on fracture load. Each of the central, mesial and distal connectors was prepared with one of 2 different cross-sectional areas and one of 3 different forms (one circular and two oval forms) to give a total of 18 designs. Five frameworks were then prepared for each design, making a total of 90. Each framework was cemented to the test model with glass ionomer cement. Fracture load was measured with a universal testing machine at a cross-head speed of 1.0 mm/min. A three-way ANOVA revealed significant differences in fracture load depending on cross-sectional area, central connector cross-sectional form, or mesial/distal connector cross-sectional form ($p < 0.01$). No interaction was observed, however, between any two connector design elements. The results of a Tukey analysis revealed a significant difference between the two connector cross-sectional areas investigated, with an increase in connector cross-sectional area resulting in an increase in fracture load. Fracture load decreased as the height of the mesial or distal connector decreased. Fracture load was significantly higher in frameworks in which the height of the central connector was greater than that of the distal or mesial connector. In conclusion, these results suggest that sufficient height needs to be maintained in the mesial/distal connector to secure a high fracture load in zirconia 4-unit all-ceramic FPDs. Moreover, even when this is not possible, a high fracture load may still be obtained by making the height of the central connector as great as possible. Furthermore, extending the connector cross-sectional area is effective in increasing fracture load.

Key words: Four-unit fixed partial dentures (4-unit FPDs) —
Yttria-stabilized tetragonal zirconia polycrystals (YTZP) —
Static load bearing tests — Connector of FPDs

Introduction

In recent years, the superior esthetic properties and biocompatibility of all-ceramic restorations has led to their increasing use in a clinical setting^{3,13,20}. Most studies involving static load-bearing tests on all-ceramic fixed partial dentures (FPDs) have focused on those with only 3 units^{2,7,8,11,12,15,16,18,19,21,22}, with few targeting 4-unit FPDs^{6,9,10}. When two consecutive teeth are missing, it is sometimes not possible to select a dental implant due to metal allergy. In such cases, if the patient wants an FPD, it is necessary to select a high strength material capable of withstanding occlusal forces. Few experimental studies have focused on 4-unit FPDs designed based on simulation of the distance between abutments in the molar region. This is probably because of the inadequate strength of 4-unit FPDs made of conventional ceramics when designed for use as cores^{1,14}.

However, due to recent advances in computer-aided design and manufacturing, yttria-stabilized tetragonal zirconia polycrystals (Y-TZP), serving as high-strength ceramics, have begun to be applied clinically, making it possible to design FPDs with a greater number of units.

The use of 4 units may enhance esthetics and hygiene in the embrasure areas of the prosthesis. However, this also decreases the cross-sectional area, making it necessary to ensure that the framework is strong enough to withstand occlusal forces. An increase in the height of the cross-sectional form results in a high fracture load⁵. In the posterior region, however, it is sometimes impossible to ensure that the height of the cross-sectional form is sufficient. In addition, 4-unit FPDs have three connectors, increasing the potential for fracture, and the central connector is located far from the abutment. The influence of the form of the central connector in relation to that of the other connectors on fracture load remains to be established. Therefore, to avoid fracture in 4-unit FPDs, it is essential to optimize the design of the connector with regard to cross-sectional area and form.

The purpose of the present study was to conduct static load-bearing tests on 4-unit Y-TZP all-ceramic FPD frameworks with different cross-sectional areas and forms to evaluate the influence of connector design (including cross-sectional area and combination of cross-sectional forms) on fracture load.

Materials and Methods

1. Materials

The material tested was 3% Y-TZP (Everest® Zirconium Soft). This type of zirconia is applicable to molar 4-unit all-ceramic FPDs.

2. Preparation of test specimens

A metallic master model was made of stainless steel to prepare 4-unit FPDs covering the second premolar (missing), first molar (missing), first premolar (abutment), and second molar (abutment). The abutment margin forms were designed as a deep chamfer with a curvature radius of 1.0 mm. The axial surface had a taper of 6°. Both abutments had a height of 5.0 mm. The angle of the axial occlusal surface was rounded with a curvature radius of 1.0 mm. From the occlusal view, the first premolar (abutment) assumed the form of a circle with a diameter of 7.0 mm, and the second molar assumed the form of a circle with a diameter of 11.0 mm. The distance between the two abutments was 27.0 mm.

An impression of the master model for the FPD abutment was taken and a working cast prepared with high strength dental stone (Everest® Rock, Kavo, Germany). Prior to designing the frameworks, the working cast was first scanned using the Kavo Everest® System (Kavo Everest® System, Kavo).

The coping of the frameworks had a thickness of 0.55 mm and cement space of 45 μ m. The pontics were designed to have a cylindrical form (semi-spherical base and flat occlusal surface). The connectors were designed so that the length of the three connectors would be equal along a straight line joining the centers of the vertical dimensions of the individual abutments, based on simulation of

Table 1 Combinations of connector type

		Central connector		
		-A-	-B-	-C-
Mesial and distal connectors	A-A	AAA	ABA	ACA
	B-B	BAB	BBB	BCB
	C-C	CAC	CBC	CCC

← 9.0 mm ² →			← 7.0 mm ² →

A = 1:1 3.39/3.39	B = 3:4 2.93/3.91	C = 2:3 2.76/4.14	A = 1:1 2.99/2.99	B = 3:4 2.58/3.44	C = 2:3 2.44/3.66
Ratio = height:width Length = height/width (mm)					

the state after attachment of the coping.

The framework connectors were designed with two cross-sectional areas (9.0 or 7.0 mm²), with that of all three connectors equal. Three different cross-sectional forms were designed: a circular form, with a height/width ratio of 1:1 (Type A); an oval form, with a height/width ratio of 3:4 (type B); and another oval form with a height/width ratio of 2:3 (type C). These connector types were applied to each of the mesial/distal connectors (A-A, B-B, C-C) and central connector (-A-, -B-, -C-). Table 1 lists the combinations of connector types tested. In total, 18 designs were tested and 5 frameworks prepared for each design (90 in total).

The abutments of each test model were placed in an abutment holder with the same dimensions as that of the master model. A silicone material with a thickness of 1.0 mm was placed between the abutment and abutment holder to act as a pseudo-periodontium.

After each framework was fabricated, the conformity of the coping was checked to ensure a good fit at the margin level using silicone impression material (Fit Checker, GC, Tokyo, Japan). Each framework was cemented to the test model with glass ionomer cement (Fuji I, GC) according to the manufacturer's instructions. The cemented frameworks were then immersed in distilled water (37°C) for 24 hrs.

3. Static load-bearing test

Static load-bearing tests were conducted with a universal testing machine (Autograph AG-I20KN, SHIMADZU, Kyoto, Japan). The load was simultaneously applied on the flat occlusal surface of the two pontics at a cross-head speed of 1.0 mm/min until the specimen fractured to determine fracture load. Two polytetrafluoroethylene (Teflon™) disks with the thickness of 2.0 mm were interposed between the loading stamp and framework as a shock absorber (Fig. 1). The Teflon™ disks were replaced with new ones for each test.

After the fracture load had been measured, the fracture site was checked. To observe the fracture site, the fractured surfaces were first coated with Au-Pd and then observed through a scanning electron microscope (SEM JSM-6340F, JEOL, Tokyo, Japan).

4. Statistical analysis

The data on fracture load were subjected to a three-way analysis of variance (three-way ANOVA) involving three parameters (connector cross-sectional area, mesial/distal connector cross-sectional form, and central connector cross-sectional form). Tukey's method was employed for multiple comparisons. The fracture site was analyzed in relation to framework design using the chi-square test (χ^2 test).

Fig. 1 Test device for determination of static load bearing of 4-unit framework

Fig. 2 Fracture load required for FPD framework

Table 2 Mean fracture load in FPD framework

Cross-sectional area	n	Mean ± SD (N)	Tukey method
9.0 mm ²	45	621.02 ± 62.86	**
7.0 mm ²	45	529.77 ± 50.62	
Mesial and distal connector's type	n	Mean ± SD (N)	Tukey method
A-A	30	597.11 ± 69.47	**
B-B	30	581.08 ± 68.08	
C-C	30	548.03 ± 74.72	
Central connector's type	n	Mean ± SD (N)	Tukey method
-A-	30	602.20 ± 67.58	* **
-B-	30	553.34 ± 70.39	
-C-	30	570.67 ± 74.50	

*p<0.05 **p<0.01

Results

Figure 2 shows the data on fracture load for each framework design. The three-way ANOVA revealed significant differences in fracture load depending on the cross-sectional area of the connector, its cross-sectional form, or the cross-sectional form of the mesial/distal connector ($p<0.01$). No interaction was observed between any two elements of the connector design, however. Table 2 shows the mean fracture load for each parameter and the results of the Tukey analysis.

When the fracture load was analyzed in relation to the cross-sectional area, it was significantly higher with a cross-sectional area of 9.0 mm² compared to that of 7.0 mm².

An analysis of fracture load in relation to the cross-sectional form of the connector revealed that it was significantly higher in frameworks with mesial/distal connector type A-A or B-B than with C-C. Fracture load was significantly higher in frameworks with central connector type -A- than those with -B- or -C-.

Tables 3 and 4 show the findings regarding

Table 3 Patterns of combination

Pattern I: BAB CAC CBC
The height of connector's cross-sectional form larger at the central than at the mesial/distal
Pattern II: ABA ACA BCB
The height of connector's cross-sectional form smaller at the central than at the mesial/distal

site of fracture analyzed in relation to connector design. Pattern I indicates frameworks in which the height of the central connector's form was greater than the height of the mesial/distal connector's cross-sectional form. Pattern II refers to frameworks in which the height of the central connector's cross-sectional form was less than the height of the mesial/distal connector's cross-sectional form.

When the connector's cross-sectional area was 9.0 mm², fracture in Pattern I frameworks often occurred at the distal connector, while fracture in Pattern II frameworks often took place at the central connector. When the cross-sectional area was 7.0 mm², fracture often occurred at the central connector in both Pattern I and II frameworks. No fracture was observed at the mesial connector in any framework with either of the two cross-sectional areas.

Discussion

In the present study, 4-unit Y-TZP FPD frameworks for molars were prepared and subjected to fracture tests. Test models were made in which the abutments were designed to correspond with an oral environment in which the first premolar and second molar were missing.

Lüthy *et al.* suggested that the generally higher fracture load capacity of immobile abutments can lead to the potential of the material being overestimated, and that cementation exerted no effect on average fracture load in FPDs¹⁰. In the present study, a test model with a mobile abutment and pseudo-

Table 4 Site of fracture

	Connector		
	Central	Distal	χ^2 test
9.0 mm ²			
Pattern I	5	10	]** (p<0.01)
Pattern II	12	3	
7.0 mm ²			
	Central	Distal	χ^2 test
Pattern I	11	4	None
Pattern II	13	2	

periodontium was adopted to simulate the oral environment, and glass ionomer cement was utilized for all copings.

Test methods have varied^{6,9,10}. In the present study, a Teflon™ disk was used as a shock absorber, and was placed on the flat occlusal surface of the two pontics to avoid any contact failure within the framework and distribute occlusal load. Scanning electron microscopy revealed wrinkles radiating from the area indicated by the arrow in Fig. 3, suggesting the origin of fracture. It was located close to the surface at the gingival embrasure of the connector, which corresponds with the results of earlier reports^{2,6,10,17}. Fracture originating in the occlusal plane was not observed in any of the frameworks tested.

Generally, it is desirable to make the cross-sectional area of the connector as large as possible. Lüthy *et al.* recommended a cross-sectional area of greater than 7.3 mm² for clinical application¹⁰. Therefore, in the present study, we adopted 7.0 mm² and 9.0 mm². The mean fracture load was 560.13–691.38 N at a cross-sectional area of 9.0 mm² and 473.88–562.75 N at 7.0 mm². Fontijn *et al.* reported that the maximum occlusal force in the posterior dentition ranged from 250 to 400 N⁴. If we assume that mastication force is 400 N, then all the frameworks tested would have survived. However, one earlier study has suggested mastication forces to be in the range of 500–1,000 N in cases where parafunctional behavior such as bruxism is present, depending on the measuring method

Fig. 3 SEM observation of fracture surface of framework

Arrow: indicates origin of radiating wrinkles.

Photographs b and c are higher magnifications of areas shown in rectangles in a and b, respectively.

and the location in the dentition¹⁰⁾. However, the environment employed here was artificial, making a direct comparison difficult.

For an FPD framework in the posterior dentition, we usually use a circular or oval form with a longer buccolingual width than occlusal

height, which under clinical conditions would be required in order to secure sufficient height. An increase in cross-sectional height results in a greater fracture load. Here, however, we assumed that the height of the cross-sectional form could not be secured, and so adopted a circular or one of two oval forms with a longer buccolingual width than occlusal height.

The three connectors could be classified into two regions, one comprising the mesial and distal connectors, which were connected to their respective abutments, and the other consisting of the central connector, which formed the pontic. Fracture load was measured in each different design.

In the mesial/distal connectors, fracture load showed a significant increase with increase in height of the cross-sectional form. This suggests that, where two consecutive teeth are missing, it is necessary that the cross-sectional area and height of the mesial/distal connectors be as great as possible in 4-unit FPD frameworks.

In the central connector, also, fracture load showed a significant increase with increase in the height of cross-sectional form. This suggests that the height of the cross-sectional form of the central connector needs to be as great as possible, even if we cannot secure sufficient height of the mesial/distal cross-sectional form.

Fracture occurred only at the central or distal connector. This finding is similar to that in the report by Larsson *et al.* and Lüthy *et al.*^{9,10)} In the present study, the fracture site was analyzed in relation to the height of the connector by dividing the frameworks into two patterns: Pattern I, in which the height of the central connector's cross-sectional form was greater than the height of the mesial/distal connector's cross-sectional form; and Pattern II, in which the former was less than the latter. When the cross-sectional area was 9.0 mm², the most frequent site of fracture was the distal connector in Pattern I, and the central connector in Pattern II.

In Pattern I with a connector cross-sectional area of 9.0 mm², we assumed that fracture

often occurred at the distal connector, because fracture load increases when the height of the central connector is greater than that of the mesial/distal connector. We predicted the same result in Pattern I with a connector cross-sectional area of 7.0 mm². However, fracture of the central connector occurred more frequently than fracture of the distal connector. The findings of the present study suggest that the height difference between the mesial/distal connectors and central connectors, resulting in a pseudo-arch structure, contributes to a change in the distribution of stress throughout the framework. In addition, it can be assumed that variation in cross-sectional shape may further complicate the interpretation of these results.

In the present study, no fracture was observed at the mesial connector. This may have been because the distance from the center of the abutment to the loading point was smaller for the mesial than for the distal or central connector, as pointed out by Tsumita *et al.*²¹⁾

The failure of FPDs with Y-TZP frameworks is clinically considered as fracture of the veneering ceramic material³⁾. This phenomenon is mainly derived from the strength and thickness of the veneering ceramics. The design of the framework is directly related to these factors. In the present study, however, the effect of veneering ceramics on fracture load was not taken into account. Further study is therefore necessary to address this issue.

Conclusion

Fracture tests were performed on 4-unit Y-TZP FPDs and the following conclusions obtained: it is important to secure the height of the mesial/distal connector's cross-sectional form where it connects with the abutment in order to increase fracture load; it is effective to secure the height of the central connector's cross-sectional form, even if it is impossible to secure the height of the mesial/distal connector's cross-sectional where it connects with

the abutment; extending the cross-sectional area of the connector is effective in increasing fracture load.

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