Effect of framework design on the surface strain of zirconia fixed partial dentures

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The purpose of this study was to evaluate the design of resin-bonded fixed partial dentures (RBFPDs) with zirconia frameworks. The abutment teeth were the upper central incisor and the canine. Three types of frameworks were fabricated as follows: 0.5-mm- and 0.8-mm-thick zirconia frameworks with grooves and holes (0.5ZrG, 0.8ZrG) and 0.5-mm-thick zirconia frameworks without grooves and holes (0.5Zr). The control group was designed as a 0.8-mm-thick metal framework with grooves and holes (0.8MG). Static loading was applied and the surface strain of the retainers was measured with strain gages. The magnitude of the principal strain of the 0.5ZrG framework was significantly lower than that of the 0.8MG and the 0.5Zr frameworks. This result suggests that the zirconia frameworks are effective for replacing a single anterior missing tooth.

Keywords: Resin-bonded fixed partial denture, Zirconia, Framework design, Strain gage

INTRODUCTION

Patients with one maxillary anterior missing tooth have three potential treatment options, which include fixed partial dentures (FPDs), removable partial dentures and implant dentures. Among these options, fixed partial dentures, which allow clinically sufficient aesthetic and functional outcomes with minimal surgical intervention, have been widely used in clinical settings.

FPDs are further categorized into two types according to the form of the retainers, which include partial coverage crowns with limited reduction of the palatal surface and complete veneer crowns. Resin-bonded fixed partial dentures (RBFPDs), which are made of metal, are widely used and require minimal intervention because the preparation of the abutment teeth is limited to the enamel. However, they also have several disadvantages. For example, aesthetic impairment may arise from bonding a metal framework to the palatal surface of the abutment teeth, which lose their natural translucency and often become grayish in color. Furthermore, minimal reduction of the enamel surface may be associated with low rigidity of the frameworks.

There is a widely accepted theory that the thickness of metal retainers should not be less than 0.7 mm to achieve sufficient rigidity of the frameworks of RBFPDs. However, a previous report showed that an enamel thickness of 0.5–0.8 mm at the middle third of the lingual surface of maxillary anterior teeth, Thus, it is not always possible to achieve a thickness of 0.7 mm.

Regarding the clinical prognoses of RBFPDs, Creugers et al. noted that the survival rate of 4,118 conventional fixed partial dentures was 74%±2% at 15 years, which was the same survival rate reached at 4 years with RBFPDs (74%±2% of 1,598 RBFPDs survived), suggesting a clinically questionable prognosis for RBFPDs. Kerschbaum et al. reported that the most frequent failures were associated with the debonding of the RBFPDs. Flexing of the metal bridge retainer generates stress on the luting cement and eventually leads to fatigue failure. Therefore, to prevent debonding, the material of the prosthesis and the retainer design are carefully chosen so that the frameworks are not easily distorted.

Because of the recent growing interest in aesthetics and metal allergies, metal-free restorations have become common treatments. In particular, all-ceramic crowns using zirconia have spread rapidly, and zirconia has been widely used in frameworks of crowns and FPDs due to its unique mechanical properties, including so-called "transformation toughening". The elastic modulus of zirconia is reported to be 210 GPa, while that of a12% Au-Ag-Pd alloy is 86 GPa. Therefore, RBFPDs using zirconia are assumed to improve the rigidity of the RBFPDs and allow them to reduce the distortion under functional loads. In other words, a zirconia framework may have the potential to reduce the amount of tooth reduction required to secure the rigidity of the framework, compared to a metal framework designed according to the traditional standard. To reduce the amount of tooth reduction is considered to have high clinical significance for the application of RBFPDs.

Hence, in this study, the influence of the thickness and the design of RBFPDs on the rigidity of zirconia frameworks were examined by evaluating surface strain.

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using simulation models. RBFPD metal frameworks that were designed according to the traditional standard were used for comparison. The purpose of the study was to determine the optimal design of RBFRDs using zirconia.

MATERIALS AND METHODS

Metal die fabrication
A jaw model (D51FE-500A-QF, Nissin Dental Products INC., Kyoto, Japan) with missing upper right lateral incisor and artificial teeth (Simple Root Tooth Model A5A-500, Nissin Dental Products INC.) was used in this study. The upper right central incisor and the canine were prepared for the application of resin-bonded fixed partial dentures (RBFPDs). Preparation of the abutment teeth was divided into the following two groups: with grooves and without grooves. The abutment teeth with grooves were prepared as follows. To confirm the reduction of the prepared abutment teeth, a silicone mold was made to duplicate the lingual side of the artificial teeth. The palatal surface was reduced to a 0.5-mm-thick veneer with a football-shaped diamond bur (117: SHOFU INC., Kyoto, Japan). Two vertical grooves (2.0 mm length and 0.5 mm depth) were prepared on both sides of the proximal surfaces with a diamond bur (K1, GC Co., Tokyo, Japan). Using a round diamond bur, the hole was prepared at the cingulum area (0.5 mm depth and 1.0 mm diameter). The four vertical grooves were nearly parallel. The abutment teeth design without grooves was the same with the exception of the grooves and the hole. Next, an impression of the abutment teeth was taken using hydrophilic vinyl polysiloxane impression materials (Examix Fine Regular Type and Regular Hard Type, GC Co.). Master model patterns were fabricated using acrylic resin (PATTERN RESIN, GC Co.) in such a way as to pour into the impressions. The patterns were buried in the phosphate-bonded investing material (SNOW WHITE, SHOFU INC.) and cast using the cobalt-chromium alloy (COBALTAN CLASP, SHOFU INC.) to fabricate the with grooves master models (Fig. 1). The master models were fixed to aluminum rings (20.0 mm length and diameter and 1.0 mm thickness) with an auto-polymerizing resin (UNIFAST III, GC Co.). The axial inclination of the abutments was 45 degrees for the loading direction.

Fabrication of the RBFPDs
An impression of the master dies was taken using hydrophilic vinyl polysiloxane impression materials to make the working cast. Using the working cast with grooves, the frameworks were fabricated for each of the three groups (n=8). The 0.5-mm- and 0.8-mm-thick zirconia (yttria-stabilized tetragonal zirconia) framework and the 0.8-mm-thick metal (12% Au-Ag-Pd alloy) framework are referred to as the 0.5ZrG, 0.8ZrG, and 0.8MG frameworks, respectively. Using the working cast without a groove, the 0.5-mm-thick zirconia frameworks (n=8) were fabricated, and they were referred to as 0.5Zr frameworks. The working casts were scanned by a laser scanner (LAVA SCAN ST, 3M ESPE, Seefeld, Germany) to fabricate the zirconia frameworks. All parts of the frameworks were designed with the software LAVATM ScanST, 3M ESPE. The cross-sectional area of the connection parts were 6.9 mm² between the central incisor and pontic and 7.1 mm² between the pontic and canine. Zirconia blocks (LAVA TM Frame, 3M ESPE) were milled on a milling machine and then sintered.

To fabricate the 0.8MG frameworks, the shape of the 0.8-mm-thick zirconia framework (0.8ZrG) was copied onto metal frameworks. The impression of the zirconia framework was taken using a plaster impression (New Fujirock, GC Co.) and hydrophilic vinyl polysiloxane impression materials (EXAFINE PUTTY TYPE, GC Co.). An acrylic resin was put on the impression materials, and the resulting patterns were cast using a silver-palladium alloy (Castwell M.C.12% Gold, GC Co.) (Fig. 2). All frameworks were adjusted to fit the master die.

1. Marginal fitting test
The fitness between all frameworks and the master dies was measured before the strain measurements. Black silicone (BITE CHECKER, GC Co.) was put in the space between the frameworks and the master dies. Then, cross-sections of the black silicone were measured using the micron depth and a height measuring machine (Micron Depth & Height Measuring Scope MODEL.KY-60, Nissho Optical Co., Saitama, Japan) at four regions (incisal, mesial, distal, and cervical margin) (Fig. 3).

![Fig. 1 Master model made of Co-Cr alloy without grooves and holes (a) and with grooves and holes (b).](image-url)
2. The testing procedure
The frameworks and the master dies were abraded with 70 µm Al₂O₃ airborne particles (2.0 bar air pressure for 10 s) and ultrasonically cleaned in deionized water for 10 min. The surfaces of the metal frameworks and the master dies were cleaned with alcohol and applied with a metal primer (ALLOYPRIMER, Kuraray Co., Tokyo, Japan) before cementing. The frameworks were cemented to the master dies with resin-based luting cement (Panavia F 2.0 TC, Kuraray Co., Tokyo, Japan), according to the manufacturer’s instructions. Then, two rosette gages (rosette gage KFG-1-120-D17-11N30C2, KYOWA ELECTRONIC INSTRUMENTS Co., Tokyo, Japan) were attached to the palatal surface of each retainer with strain gage cement (cc33A, KYOWA ELECTRONIC INSTRUMENTS Co.) using finger pressure for 1 min (Fig. 4). These specimens were stored at room temperature for 24 h. Using a universal testing machine (Autograph AGS-H, Shimadzu Co., Tokyo, Japan), the specimens were loaded with a crosshead.
speed of 1.0 mm/min up to 200 N using a stainless rod with a ball-end (φ2.0 mm). The loading direction was at 45 degrees to the long axis of the abutment teeth, and the load was applied onto the center of the pontic (Fig. 5). The outputs from the strain gages were recorded with a sensor interface (300B, KYOWA ELECTRONIC INSTRUMENTS Co.). Then, the magnitudes of the maximum and minimum principal strain ($\varepsilon_{\text{max}}$, $\varepsilon_{\text{min}}$) were calculated as follows:

$$
\varepsilon_{\text{max}} = \frac{1}{2} \left( \varepsilon_a + \varepsilon_c \right) + \frac{1}{2} \sqrt{(\varepsilon_a - \varepsilon_c)^2 + (2\varepsilon_b - \varepsilon_a - \varepsilon_c)^2}
$$

$$
\varepsilon_{\text{min}} = \frac{1}{2} \left( \varepsilon_a + \varepsilon_c \right) + \frac{1}{2} \sqrt{(\varepsilon_a - \varepsilon_c)^2 + (2\varepsilon_b - \varepsilon_a - \varepsilon_c)^2}
$$

$$
\tan 2\theta = \frac{2\varepsilon_b - \varepsilon_a - \varepsilon_c}{\varepsilon_a - \varepsilon_c}
$$

where $\varepsilon_a$, $\varepsilon_b$, and $\varepsilon_c$ were the strains of each gage component. The Rosette strain gage was composed of three linear gages placed at 0-, 45-, and 90-degree positions. Positive values indicate a tensile strain and negative values indicate a compressive strain.

3. Statistical analyses
A two-way analysis of variance (ANOVA) and a t-test with Bonferroni correction were used for the statistical analysis of strain and fitness, with a significance level at $\alpha=0.05$.

RESULTS

Measurement of marginal fitness
The mean and standard deviation of the marginal fitness at the four regions in each tooth observed using the micron depth and height measuring machine are shown in Table 1. The two-way (teeth and regions) ANOVA detected no significant interactions among all factors in the marginal fitness results.

Strain analysis
To clarify the effect of the framework materials and the thickness on the surface strain, the magnitude of the principal strains of the zirconia frameworks (0.5ZrG, 0.8ZrG) and the metal frameworks (0.8MG) were calculated from the strains of each gage component (Fig. 6).

In the central incisor, the mean value and standard

![Fig. 5 Specimens were fixed and loaded at 45 degrees to the long axis with the universal testing machine up to 200 N, and the strain was measured.](image-url)

<table>
<thead>
<tr>
<th>Groups</th>
<th>Fitness of the frameworks (µm) (Mean±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5ZrG</td>
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<tr>
<td>Region of the margin</td>
<td></td>
</tr>
<tr>
<td>I1</td>
<td>74.4(3.45)</td>
</tr>
<tr>
<td>I2</td>
<td>35.2(2.30)</td>
</tr>
<tr>
<td>I3</td>
<td>35.9(2.46)</td>
</tr>
<tr>
<td>I4</td>
<td>34.7(3.07)</td>
</tr>
<tr>
<td>C1</td>
<td>60.5(9.46)</td>
</tr>
<tr>
<td>C2</td>
<td>34.8(3.20)</td>
</tr>
<tr>
<td>C3</td>
<td>35.4(2.53)</td>
</tr>
<tr>
<td>C4</td>
<td>35.4(3.57)</td>
</tr>
</tbody>
</table>
deviation of the 0.5ZrG, 0.8ZrG and 0.8MG frameworks were 43.8±11.3 µε, 49.3±12.9 µε, and 86.5±19.1 µε, respectively. The zirconia framework had a significant effect on decreasing the surface strain in the central incisor, compared to the metal framework. In the case of zirconia, framework thickness had no significant effect on the surface strains.

In the canine, the mean value for the 0.5ZrG, 0.8ZrG and 0.8MG groups were 24.3±4.6 µε, 25.1±2.2 µε, and 34.6±8.1 µε, respectively. There were no significant differences among the 0.8ZrG, 0.5ZrG and 0.8MG groups.

To evaluate the difference in surface strain between the central incisor and the canine, we compared the magnitude of the principal strains of each tooth. The magnitude of the principal strain of the canine was significantly lower than that of the central incisor.

To evaluate the effect of groove preparation on the surface strains, we measured the magnitude of the principal strains of the frameworks with grooves (0.5ZrG) and without grooves (0.5Zr). The magnitudes of the principal strain of the zirconia frameworks with grooves and without grooves are shown in Fig. 7.

The mean magnitude of the principal strain value and the standard deviation of the 0.5Zr framework in the central incisor and canine were 72.4±13.7 µε and 46.8±14.1 µε, respectively. The preparation of the grooves and hole in the abutment teeth had a significant effect on decreasing the surface strain of the frameworks. In each group, the magnitude of the principal strain in the central incisor was significantly higher than that in the canine.

**DISCUSSION**

There have been a number of studies investigating the effect of framework design on surface strain. Both the framework thickness and the retainer design affect framework deformation, though the mechanisms of these effects might be different. The framework deformations under a static load have been analyzed using finite element methods (FEMs), photoelastic techniques and strain gage methods. Advantages of FEMs have been reported to include accurate modeling of complex geometry, systematic model modification, and analysis of the stress-strain patterns induced in internal structures. Because it is a purely numerical method, the FEM is based on many limiting assumptions. Validation of results, however, is not always experimentally easy. Strain gage methods can directly measure stresses and strains of real materials under static loads induced by occlusal forces *in vivo*. We have previously reported the surface strain of metal crowns and FPDs *in vitro* and *in vivo* by means of a strain gage. We could successfully measure the surface strain of the prosthesis in response to static mechanical loads and reported no significant difference in surface strain between the *in vivo* and *in vitro* models. In the present study, in an attempt to obtain insight into the effect of RBFPDs framework design on the rigidity of the framework, the magnitude of the principal strain of the zirconia frameworks was analyzed using strain gage methods.

**Marginal fitness**

A poor marginal gap in the prosthesis would cause framework deformation, which leads to wash-out of the luting cement and detachment of the prosthesis. For a good long-term prognosis, the clinically acceptable marginal gap for a crown is said to be within the range of 120 µm. In the present study, the marginal gap of both the zirconia and metal frameworks were approximately 80 µm, indicating no effect of marginal adaptation on the surface strain of the frameworks.

**Experimental condition**

The load was only applied onto the pontic in this study. Motta et al. reported that the highest values of strain appeared on the connector areas between the abutments and the pontic when the loads applied on the pontic region. This reports proposed that the framework may be largest deformed when the pontic was only loaded. For these reasons, experimental conditions were set up...
most severe in this study.

**Strain analysis**

The preparation of the RBFPDs should be confined to the enamel as much as possible, and the thickness of the framework is limited by the interocclusal space. Therefore, the thickness of the retainer is directly influenced by the occlusion and enamel thickness before the exposure of the dentin. In addition, this concept of minimal intervention dentistry is a modern dental practice designed around the principal aim of preservation of the natural tooth structure as much as possible. However, the approach of minimal tooth reduction leads to a thin framework. It has been suggested that a thin framework is easy to fracture or transform and that the stress concentrates on the resin-metal interface. Consequently, RBFPDs will be debonded at regular masticatory loads. Thus, some previous reports have shown that the thickness of the metal frameworks should not be less than 0.7 mm.

Generally, it is believed that framework deformation is determined by the moment of force, the elastic modulus and the section modulus. In the present study, zirconia with a high elastic modulus (210 GPa) decreased the framework deformation more than the 12% Au-Ag-Pd alloy with a low elastic modulus (86 GPa). Furthermore, surface strains of the thin framework (0.5ZrG) decreased the framework deformation compared with the conventional metal framework (0.8MG), indicating the viability of the clinical application of a thin framework using zirconia and reduced teeth preparation.

Generally, proximal grooves have been demonstrated to enhance the retention of RBFPDs by increasing the attachment surface area and by mechanical locking; these grooves have also been shown to improve the long-term prognosis of anterior RBFPDs. Additionally, framework rigidity has been reported to enhance the retention/resistance of RBFPDs. Although the groove placement could successfully suppress the surface strain of the retainers (0.5ZrG vs. 0.5Zr), the framework deformation of the zirconia framework without grooves (0.5Zr) was equal to that of the conventional metal framework with grooves (0.8MG).

Inadequate retention may result from many factors, including an underdeveloped cingulum. If debonding occurs over and over again, it may be necessary to remake the RBFPD. In these cases, even if the RBFPDs were made of zirconia, it is necessary to add the retentive forms to the preparation. Generally, the majority of dislodged two-retainer RBFPDs debonded only on one abutment. It was assumed that the retainer of the central incisor was more likely to debond than the canine because, in this study, the magnitude of the principal strain in the central incisor was significantly higher than that in the canine. One of the reasons for the result was due to a difference in the tooth morphologies. In particular, the maxillary canines have a well-developed cingulum, which conferred a convex lingual contour on the retainer. Ibrahim et al. said that this convex lingual contour might confer rigidity on the retainer, which results in the retainer being less capable of resisting torqueing force.

In the case of debonding without caries, the RBFPD may be rebonded without discomfort to the patient, and the rebonded RBFPD is more susceptible to dislodgement than the originally bonded RBFPD. Therefore, it is necessary to reconsider the design of RBFPDs. The previous reports discussed ways to improve the retention of the RBFPDs. Some reports showed that the retention is dependent on additional retentive forms and the actual surface area covered by the retainer with the bonding agent. In this study, the magnitude of the principal strain in the central incisor was significantly higher than that in the canine. Therefore, it is necessary to add the retentive forms to the central incisor in advance or during the remaking of the RBFPDs.

**CONCLUSION**

Within the limitations of this in vitro study, the RBFPDs using 0.5-mm-thick zirconia framework is effective method for the anterior single missing tooth because of the less amount of tooth reduction compared with that of using metal framework. Furthermore, when the RBFPDs are made of zirconia, the grooves and hole has been purported to decrease the distortion on equality with the traditional metal. However, the effect of the reduction of framework thick on the mechanical strength will also be examined using fracture test and the clinical evaluation will be further investigated.

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