The influence of the framework thickness on surface strain of the 3-unit zirconia resin-bonded fixed dental prostheses under the functional loading

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Purpose: The purpose of the present study was to optimize the form of a resin-bonded fixed dental prosthesis (RBFDP) frame by preparing various framework designs using ceria-stabilized tetragonal zirconia/alumina nano composite (Ce-TZP/Al) materials.
Materials and Methods: Six types of frameworks were fabricated as follows: 0.8-mm-thick metal (0.8M), 0.8-mm- and 0.5-mm-thick yttria-stabilized tetragonal zirconia polycrystal frameworks (0.8Y, 0.5Y) and 0.8-mm-, 0.5 -mm- and 0.3-mm- thick Ce-TZP/Al frameworks (0.8C, 0.5C, 0.3C). A load up to 200 N crosshead speed of 1.0 mm/min was applied to center of the palatal surfaces of the pontic of the RBFDPs by a universal testing machine. The strains of the RBFDPs during loading were measured and recorded by sensor interfaces. Then, the magnitudes of the maximum and minimum principal strain were calculated. A two-way analysis of variance (ANOVA) and a t-test with Bonferroni correction were used for the statistical analysis of strain, with a significance level at $\alpha = 0.05$.
Results: In the canine, the magnitudes of the maximum principal strain of 0.8M were significantly higher than those in group 0.8Y. There were no significant differences among the 0.3C, 0.5Y, and 0.8M groups.
Conclusion: This report suggested that Ce-TZP/Al can improve the long-term prognosis of resin bonded fixed dental prostheses in the oral cavity due to its desirable mechanical and hydrothermal degradation-resistant characteristics, enabling the design of a resin bonded fixed dental prosthesis frame with a thickness of 0.3 mm.
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Key Words: resin-bonded fixed dental prosthesis, strain gage, zirconia ceramics

Introduction

Fixed dental prostheses are widely used in clinical settings to provide prosthetic dental treatment to patients with anterior tooth loss because they restore functionality, provide good esthetics, and are comfortable. Resin-bonded fixed dental prostheses (RBFDPs), which in principle limit plasia to enamel formation [1,2] and preserve healthy tooth substances, are widely utilized since minimal intervention concept [3] is required. However, current RBFDPs using gold-silver-palladium and chromium-cobalt system alloys have limitations. For example, they cannot achieve sufficient esthetics [4,5] and may cause metal-induced allergy due to elution of metal ions.

Since yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) is superior in bend strength and esthetics, and does not cause metal-induced allergy, its clinical application has expanded. In addition, owing to improvements in the precision of abutment tooth scanning, design, and milling, a framework for RBFDPs can be made. To investigate the clinical application of RBFDPs with Y-TZP, we measured the distortion of Y-TZP using a strain gage and reported excellent stress-relaxation [6].

However, one study has stated that exposure of Y-TZP to the oral cavity is not preferable since it causes the phenomenon of hydrothermal degradation, in that a lattice constant varies due to an invasion of OH- ions into the oxygen vacancy of zirconia and hydrolysis [7,8]. This leads to phase transition from a tetragonal to monoclinic phase, and reduced physical strength. In contrast, a ceria-stabilized tetragonal zirconia/alumina nano composite (Ce-TZP/Al) eliminates the oxygen vacancy using CeO_2 as a stabilizer of ZrO_2 that drastically improves its tolerance to hydrothermal degradation compared with Y-TZP [9-11]. In addition, since the physical strength resulting from the phase transformation mechanism is not expected to improve with Ce-TZP alone, Ce-TZP/Al contains and scatters approximately 20% of alumina across the polycrystalline substance, which leads to improvement in physical strength [10].

Given the above, Ce-TZP/Al causes no hydrothermal degradation and has superior long-term stability in the oral cavity compared with Y-TZP. Furthermore, the fracture toughness of Ce-TZP/A is approximately from 2 to 3 times compared with that of Y-TZP. When Ce-TZP/Al has been used as zirconia crown framework in previous studies, even a framework thickness of 0.3 mm, which is thinner than the conventional metal crown framework, has been suggested to provide sufficient strength for use in a clinical setting [12]. Therefore, it is expected that Ce-TZP/Al materials have application in RBFDPs frameworks. The aim of the present study was to optimize the form of a RBFDPs framework by preparing various framework designs using Ce-TZP/Al materials, and measure the surface distortion.

Materials and Methods

Master model fabrication

A human dry maxilla was used in this study. It had been donated for scientific research to Maxillofacial Anatomy, Department of Maxillofacial Biology, Maxillofacial/Neck Reconstruction, Graduate School, Tokyo Medical and Dental University (TMDU). It does not have the defect of the bone, and the teeth remain in a healthy state and the personal information cannot be identified. This study was approved by the ethics review committee of TMDU (No. 1173).

To obtain the Digital Imaging and Communication in Medicine (DICOM) data of the maxilla, micro computed tomography (μCT) imaging taken by Micro focus X-ray computer tomography system (inspeXio SMX-100CT, Shimadzu Co., Ltd, Kyoto, Japan) were used. The data were in a range of the maxillary left central incisor to the maxillary left canine including their surrounding alveolar bone. The DICOM data was converted into the Standard Triangulated Language (STL) data, and then trim the maxillary left lateral incisor. Three-dimensional printer (Objet500 Connex, Stratasys, Minneapolis, MN, USA) with the STL data provided the model that the teeth can be removed from the alveolar bone.

The maxillary left central incisor and the canine were prepared for the application of RBFDPs. The palatal surfaces were prepared with a diamond football-shaped point (117, Shofu Inc., Kyoto, Japan) at the regulated thickness (0.3 mm and 0.5 mm). Cervical preparations were performed by a diamond chamfer point (K1, GC Co., Tokyo, Japan) within its 1.0 mm from the anatomical cervical lines. The finish lines were designed as chamfer having the same thickness as the palatal surfaces. Two vertical grooves (0.5 mm depth) were prepared both sides of proximal surfaces and a hole (1.0 mm diameter and 0.5mm depth) were prepared on the cingulum areas with a diamond round point (MI-2R, Shofu Inc.).

To duplicate the abutment teeth, impressions of the abutment teeth were made with vinyl polysiloxane impression material (Memosil2, Heraeus-Kulzer GmbH, Hanau, Germany). Then an auto-mix resin composite (Clearfil DC Core Automix One, Kuraray Noritake Dental Inc., Tokyo, Japan) was injected into the impressions.

Fabrication of RBFDPs

The 0.8-mm-thick gold-silver-palladium alloy (Castwell M.C.12%Gold, GC Co.) frameworks (0.8M), 0.5-mm- and 0.8-mm-thick Y-TZP (C-Pro HTZR, Panasonic Healthcare Co., Ltd, Tokyo, Japan) frameworks (0.5Y, 0.8Y) and 0.3- mm-, 0.5 -mm- and 0.8- mm- thick Ce-TZP/Al (C-Pro Nanozr, Panasonic Healthcare Co., Ltd,) frameworks (0.3C, 0.5C, 0.8C) were defined as the experimental groups. Each groups consisted of 5 specimens.

To design and fabricate RBFDPs using zirconia (0.5Y, 0.8Y, 0.3C, 0.5C, 0.8C), the resin abutment teeth were scanned by a dental laboratory scanner (3Shape D700, 3Shape, Copenhagen, Denmark). The RBFDPs using zirconia were designed respectively using the three-dimensional data of the corresponding resin abutment teeth. The cross-sectional area of the connectors was defined as 6.0 mm^2, and the design of the shape was elliptical. The cement layer thickness was determined to 40 µm in the range from the margin to 1.0 mm, in the other sites 20 µm. The RBFDPs using zirconia were designed uniform thickness according to the rule of the experimental group (Fig. 1).

Fig. 1 Photographs of framework; Metal (a), Y-TZP (b), and Ce-TZP (c)

Impressions of 0.8Y were made with vinyl polysiloxane impression material (Exafine putty type, GC Co.) and improved dental stone (New Fujirock, GC Co.). Acrylic resin (Pattern Resin, GC Co.) was injected among the putty and the dental stone to obtain the resin pattern of RBFDPs using metal. The resin pattern of 0.8M were invested with an investment material (Cristobalite PF, Shofu Inc.) and cast in gold-silver-palladium alloy (12%Au-Ag-Pd alloy) with vacuum casting machine (KDF Cascom, Denken Co., Ltd. Kyoto, Japan).

Testing procedure

The frameworks and the master dies were abraded with 70 µm Al_2O_3 airborne particles (0.2 MPa air pressure for 10 s) and ultrasonically cleaned in deionized water for 10 min. The surfaces of the resin abutment teeth and frameworks using zirconia were cleaned with alcohol and applied with a ceramic primer (Clearfil Ceramic Primer plus, Kuraray Noritake Dental Inc.) and the surfaces of the 0.8M were cleaned with alcohol and applied with a metal primer (Alloy Primer, Kuraray Noritake Dental Inc.). Then, the RBFDPs were cemented to the resin abutment teeth with resin-based luting cement (Panavia F2.0 TC, Kuraray Noritake Dental Inc.) according to the manufacturer's instructions.

The buccal surfaces of the RBFDPs were sandblasted and ultrasonically cleaned with the same way as previous process. Rosette gages (KFG-1-120-D17-11 N30C2, Kyowa Electronic Instruments Co., Tokyo, Japan) were bonded to the center of the buccal surfaces of the maxillary left central incisor and the canine of the RBFDPs with strain gage cement (cc33-A, Kyowa Electronic Instruments Co.) using finger pressure for 1 min on polyethylene film (Fig. 2).

The resin abutment teeth were embedded in acrylic resin base (Palapress Vario, Heraeus-Kulzer GmbH). Each root was surrounded with a layer of vinyl polysiloxane impression material (Correct Plus Bite, Pentron Co., Wallingford, CT, USA) as the artificial periodontal ligament (approximately 0.25 mm), and the angles between the roots and the horizontal plane were determined to 45˚.

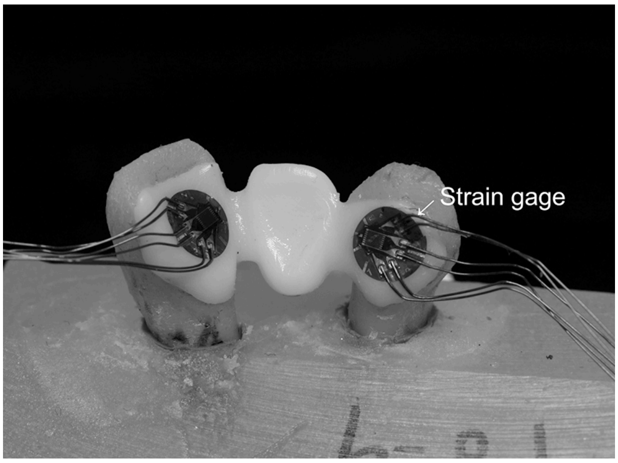

Fig. 2
The palatal aspect of framework with two strain gages bonded to the palatal surface of each retainer

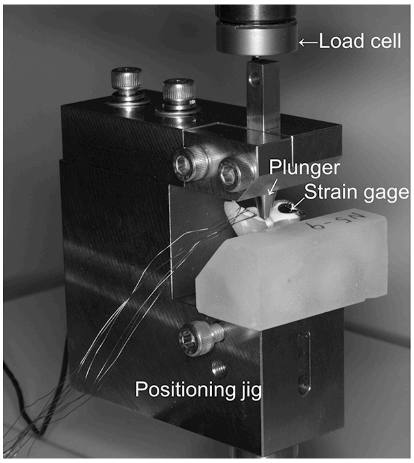

Fig. 3
Stress strain test scenario
Specimens were fixed and loaded at 45˚ to long axis with the universal testing machine up to 200 N.

Stress strain test

A load up to 200 N with crosshead speed of 1.0 mm/min was applied to center of the palatal surfaces of the pontic of the RBFDPs by a universal testing machine (Autograph AGS-H, Shimadzu Co., Ltd, Kyoto, Japan) with a stainless rod with ball-end (φ2.0mm) (6x6x40, KDA Co., Tokyo, Japan) (Fig. 3). The loading direction was at 45˚ to the long axis of the abutment teeth. The strains of the RBFDPs during load were measured and recorded by sensor interfaces (PCD-300B, PCD-330B-F and PCD-300A, Kyowa Electronic Instruments Co.). Then, the magnitudes of the maximum and minimum principal strain (εmax, εmin) were calculated as follows:

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

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

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

εa, εb and εc were the strains of each gage component.

Statistical analyses

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

Results

To clarify the effect of the framework materials and the thickness on the surface strain, the magnitude of the principal strains of the metal frameworks (0.8M), the Y-TZP frameworks (0.8Y, 0.5Y), and the Ce-TZP/Al frameworks (0.8C, 0.5C, 0.3C) were calculated from the strains of each gage (Fig. 4). In the canine, the mean value for the metal frameworks (0.8M), the Y-TZP frameworks (0.8Y, 0.5Y) and the Ce-TZP/Al frameworks (0.8C, 0.5C, 0.3C) were 261.6 ± 55.1 με, 141.5 ± 40.7 με, 205.5 ± 83.0 με, 180.7 ± 41.6 με, 202.5 ± 50.5 με, and 216.8 ± 35.2 με respectively. The magnitudes of the maximum principal strain in group 0.8M were significantly higher than those in group 0.8 Y-TZP frameworks. There were no significant differences among the 0.3N, 0.5Y, and 0.8M groups.

In the central incisor, the magnitude of the principal strains of the metal frameworks (0.8M), the Y-TZP frameworks (0.8Y, 0.5Y), and the Ce-TZP/Al frameworks (0.8C, 0.5C, 0.3C) were 52.8 ± 45.3 με, 44.1 ± 42.8 με, 33.8 ± 64.4 με, 55.7 ± 35.7 με, 0.1 ± 39.8 με, and −21.7 ± 70.8 με respectively. In all the groups, there was no significant difference between the groups. In all groups, the framework of the canine showed a larger distortion than that of the central incisor.

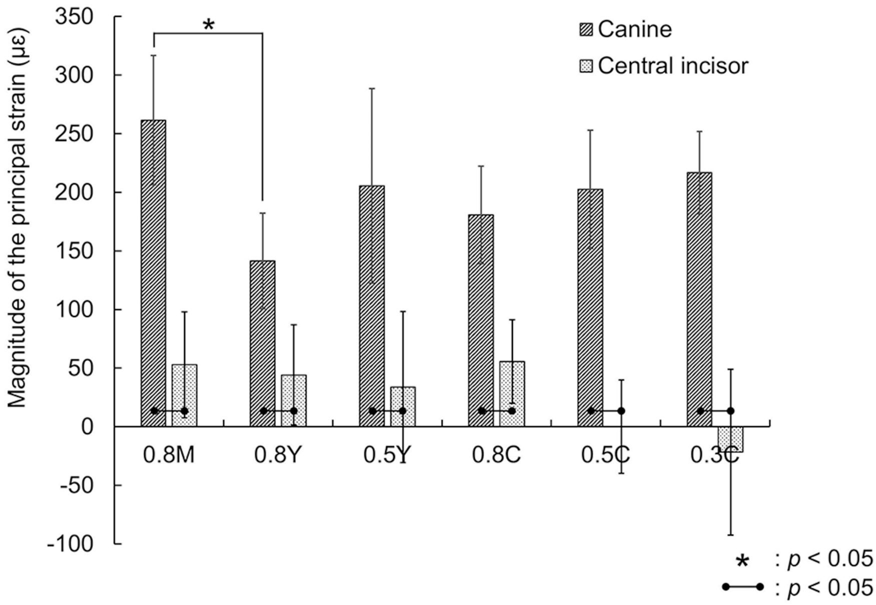

Fig. 4 Comparison of magnitude of the principal strains for six kinds of frameworks

Discussion

To optimize the framework design of RBFDPs manufactured using Ce-TZP/Al, we examined the transformation of RBFDPs framework via the in vitro strain gage method. The transformation of the framework under the dead load was analyzed using a finite element method, photoelasticity method, and strain gage method. In the strain gage method, it is possible to attach a strain gage to the prosthesis, and measure its stress and distortion directly [13,14]. This allows the evaluation of the transformation during the functioning of the prosthesis used in clinical settings. Previously, we examined the surface distortion of crown and partial dentures in vitro and in vivo using the strain gage, and reported no change in the transformation of the framework in each experimental model [15]. This highlighted the importance of the examination method for the design of the framework in vitro.

With regard to the in vitro experimental model, a human dry skull was scanned using μCT, and a model of an abutment tooth and alveolar bone was created using a three-dimensional printer. This method is believed to measure the distortion of the framework more accurately because it precisely mimics the conditions such as the form of the alveolar bone and the planting direction of the abutment tooth. In this study, 200 N, assumed to be the greatest biting force of the anterior teeth [16], was loaded on a pontic. Generally, for occlusal adjustment of RBFDPs, the biting force applied is balanced between the pontic and the abutment tooth. However, in this experimental model, the greatest biting force of the anterior teeth was loaded on only the pontic in order to conduct an analysis under a severe condition comparable to that in the oral cavity.

A RBFDPs using Ce-TZP/Al can be designed with a thickness of 0.3 mm, based on the excellent mechanical strength of Ce-TZP/Al. Considering that Y-TZP must be designed with a thickness of at least 0.5 mm in order to prevent breakage, due to its mechanical strength and milling, a reduction in the abutment tooth substance deletion can be expected using Ce-TZP/Al. The general enamel thickness is 0.5-0.8 mm [17], and dentin can be exposed depending on its form. In exposed dentin, the adhesive strength may be reduced [18] and caries may advance rapidly. Therefore, a reduction in deleted tooth substances using Ce-TZP/Al can improve the long-term prognosis.

In the present study, based on the above conditions, various designs of Ce-TZP/Al were created and the surface distortion was measured. Results indicated a tendency similar to the distortion of RBFDPs made using an alloy, and suggested potential clinical application. Detachment of the prosthesis is a main factor contributing to reduced survival rate of RBFDPs. When a functional force such as masticatory force acts on the prosthesis, the framework is transformed, applying detachment power to the adhesive interface [19,20]. Examination of the third maximal distortion revealed that the 0.8 mm-thick framework created using Y-TZP reduced the surface distortion more prominently compared with the framework made from an alloy. However, there was no statistical significance between Y-TZP frameworks with a thickness of 0.5 mm and Ce-TZP/Al frameworks of various thicknesses.

The framework of the canine tooth showed a larger distortion than that of the central incisor in all groups. The distortion of the framework was determined based on the moment, elasticity coefficient, and section modulus. This could be due to the fact that the model canine tooth, prepared based on CT scan data of a human dry-toothed jawbone in order to reproduce the oral cavity more precisely, was slightly twisted. This resulted in a tendency for moment to be produced easily when a load was applied to the pontic; the adhesion area was 103 mm^2 and 75 mm^2 at the central incisor and the canine tooth, respectively. Considering that surface distortion may be reduced by providing supportive abutment pieces, such as a groove or hole to the abutment tooth [21-24], it is thought to be desirable to provide such pieces to the abutment tooth when stress appears to be concentrated in one abutment tooth, as in the case of the present study.

Based on the above findings, it is suggested that Ce-TZP/Al can improve the long-term prognosis of RBFDPs in the oral cavity due to its desirable mechanical and hydrothermal degradation-resistant characteristics, enabling the design of a RBFDPs framework with a thickness of 0.3 mm.

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References

1. Corrente G, Vergnano L, Re S, Cardaropoli D, Abundo R. Resin-bonded fixed partial dentures and splints in periodontally compromised patients: a 10-year follow-up. Int J Periodontics Restorative Dent 2000; 20: 628-36.
2. Wyatt CC. Resin-bonded fixed partial dentures: what's new? J Can Dent Assoc 2007; 73: 933-8.
3. Tanaka K, Tamura J, Kawanabe K, Nawa M, Uchida M, Kokubo T, et al. Phase stability after aging and its influence on pin-on-disk wear properties of Ce-TZP/Al2O3 nanocomposite and conventional Y-TZP. J Biomed Mater Res A 2003; 67: 200-7.
4. Botelho M. Resin-bonded prostheses: The current state of development. Quintessence Int 1999; 30: 525-34.
5. Rosentritt M, Kolbeck C, Ries S, Gross M, Behr M, Handel G. Zirconia resin-bonded fixed partial dentures in the anterior maxilla. Quintessence Int 2008; 39: 313-9.
6. Nemoto R, Nozaki K, Fukui Y, Yamashita K, Miura H. Effect of framework design on the surface strain of zirconia fixed partial dentures. Dent Mater J 2013; 32: 289-95.
7. Chevalier J, Gremillard L, Virkar AV, Clarke DR. The tetragonal-monoclinic transformation in zirconia: Lessons learned and future trends. J Am Ceram Soc 2009; 92: 1901-20.

8. Kim JW, Covel NS, Guess PC, Rekow ED, Zhang Y. Concerns of hydrothermal degradation in CAD/CAM zirconia. J Dent Res 2010; 89: 91-5.
9. Tanaka K, Tamura J, Kawanabe K, Nawa M, Uchida M, Kokubo T, et.al. Phase stability after aging and its influence on pin-on-disk wear properties of Ce-TZP/Al_2O_3 nanocomposite and conventional Y-TZP. J Biomed Mater Res A 2003; 67: 200-7.
10. Ban S, Suehiro Y, Nakanishi H, Nawa M. Fracture toughness of dental zirconia before and after autoclaving. J Ceram Soc Jpn 2010; 118: 406-9.
11. Marro FG, Mestra A, Anglada M. Contact damage in a Ce- TZP/Al_2O_3 nanocomposite. J Eur Ceram Soc 2011; 31: 2189-97.
12. Omori S, Komada W, Yoshida K, Miura H. Effect of thickness of zirconia-ceramic crown frameworks on strength and fracture pattern. Dent Mater J 2013; 32: 189-94.
13. Sato Y, Yuasa Y, Abe Y, Akagawa Y. Finite element and Weibull analysis to estimate failure risk in resin-bonded retainers. Int J Prosthodont 1995; 8: 73-8.
14. Ziada HM, Orr JF, Benington IC. Photoelastic stress analysis in perforated resin bonded bridge design. J Oral Rehabil 2000; 27: 387-93.
15. Yamashita J, Shiozawa I, Takakuda K. A comparison of in vivo and in vitro strain with posterior fixed partial dentures. J Prosthet Dent 1997; 77: 250-5.
16. Paphangkorakit J, Osborn JW. The effect of pressure on a maximum incisal bite force in man. Arch Oral Biol 1997; 42: 11-7.
17. Ferrari M, Cagidiaco C, Bertelli E. Anatomic guide for reduction of enamel for acid-etched retainers. J Prosthet Dent 1987; 58: 106-10.
18. Durey KA, Nixon PJ, Robinson S, Chan MFWY. Resin bonded bridges: techniques for success. Br Dent J 2011; 211: 113-8.
19. Ibbetson R. Clinical considerations for adhesive bridgework. Dent Update 2004; 31: 254-6, 258, 260.
20. Rosentritt M, Ries S, Kolbeck C, Westphal M, Richter E-J, Handel G. Fracture characteristics of anterior resin-bonded zirconia-fixed partial dentures. Clin Oral Investig 2009; 13: 453-7.
21. Simon JF, Gartrell RG, Grogono A. Improved retention of acid-etched fixed partial dentures: a longitudinal study. J Prosthet Dent 1992; 68: 611-5.
22. Saad AA, Claffey N, Byrne D, Hussey D. Effects of groove placement on retention/resistance of maxillary anterior resinbonded retainers. J Prosthet Dent 1995; 74: 133-9.
23. Behr M, Leibrock A, Stich W, Rammelsberg P, Rosentritt M, Handel G. Adhesive-fixed partial dentures in anterior and posterior areas. Results of an on-going prospective study begun in 1985. Clin Oral Investig 1998; 2: 31-5.
24. Nair A, Regish KM, Patil NP, Prithviraj DR. Evaluation of the effects of different groove length and thickness of the retainers on the retention of maxillary anterior base metal resin bonded retainers -an in vitro study. J Clin Exp Dent 2012; 4: e91-6.

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