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Effect of different surface treatments and retainer designs on the retention of posterior Pd-Ag porcelain-fused-to-metal resin-bonded fixed partial dentures

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Abstract. The aim of this study was to investigate the adhesive property of palladium-silver alloy (Pd-Ag) and the simulated clinical performance of Pd-Ag porcelain-fused-to-metal (PFM), resin-bonded, fixed partial dentures (RBFPDs). A total of 40 Pd-Ag discs (diameter=5 mm) were prepared and divided into the following four groups (n=10): a) No sandblasting, used as a control; and b, 50 μm; c, 110 μm; and d, 250 μm aluminum oxide (Al_2O_3) particles, respectively. Another 50 discs were pre-sandblasted and divided into five groups (n=10) subjected to different treatments: e) Sandblasting, used as a control; f) silane; g) alloy primer; h) silica coating + silane and i) silica coating + alloy primer. All 90 discs were bonded to enamel with Panavia F 2.0 and then subjected to shear bond strength (SBS) testing. The fracture surfaces were examined by scanning electron microscopy. Next, 40 missing maxillary second premolar models were restored with one of the four following RBFPD designs (n=10): I) A premolar occlusal bar combined with molar double rests (MDR); II) both occlusal bars with a wing (OBB); III) a premolar occlusal bar combined with a molar dental band (MDB); and IV) two single rests adjacent to the edentulous space with a wing (SRB) used as a control. All specimens were aged with thermal cycling and mechanical loading. Subsequently, they were loaded until broken. The data were analyzed by one-way analysis of variance. Al_2O_3 (250 μm) abrasion provided the highest SBS ($P<0.05$). The alloy primer and silica + silane exhibited increased SBS. Furthermore, fracture analysis revealed that the failure mode varied among the different treatments. Whereas MDB exhibited the highest retention ($P<0.05$), that of OBB was greater than that of MDR ($P<0.05$), and the control exhibited the lowest retention. Abrasion with Al_2O_3 (250 μm) effectively increased the adhesive property of Pd-Ag. Additionally, treatment with the alloy primer and silica coating + silane was able to increase the adhesive property of abraded Pd-Ag. Under the present conditions, all three modified retainer types provided improved outcomes for Pd-Ag PFM RBFPDs compared with the control.

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Introduction

Resin-bonded fixed partial dentures (RBFPDs) are prostheses that are retained by bonding to acid-etched abutments with resin adhesive systems. Due to the minimally invasive preparation of the abutment teeth, RBFPDs have received much more positive attention compared to their first appearance in the dental clinic in 1973 (1). The abutment teeth for RBFPDs should be minimally prepared within the enamel (1), in which the retainers acquire stronger retention from total-etching and bonding techniques. The advantages of RBFPDs include simplified and conservative tooth preparation procedures and little-to-no injuries to the pulp (1-3).

In the posterior edentulous area, implant-supported crowns are widely accepted and have become preferred in clinical settings. However, certain areas of the edentulous space are too narrow to allow tooth implantation. In addition, some patients cannot undergo the surgery due to systemic disease (4). In such patients, RBFPDs should be considered. Posterior RBFPDs not only need to be adequately adhered, but also require high mechanical strength to withstand dislodging forces (5,6). Therefore, RBFPDs with a metal-ceramic framework are still applied (7-9).

Palladium-silver alloy (Pd-Ag) is a widely used dental alloy with sufficient casting precision and biocompatibility (10-12). In addition, its mechanical properties are adequate for application in crowns and posterior fixed dental prostheses (FDPs) (13). However, as a combination of noble metals, the alloy requires surface treatment to improve its bonding, particularly when it is fabricated into resin-bonded prostheses (14).

Airborne particle abrasion consists of sandblasting the surface of a material with aluminum oxide (Al_2O_3) particles or powder, and is an effective way to improve the adhesive ability and retention of metals and ceramics. However, the most effective particle size varies for different materials (15-18). Additionally, hydrofluoric acid etching combined with the use of a silane primer is a reliable technique for enhancing the retention of glass-ceramic prostheses (19). For noble alloys, a metal primer has been confirmed to effectively increase the bond strength between the alloys and other materials (20). The use of a silica coating in combination with silane increasing the adhesion of Pd-Ag was assessed in the present study, and this technique was compared with the use of an alloy primer coating. To increase the retention and survival rates, dual-cured luting cements, including Panavia F 2.0, are typically used in minimally invasive adhesive restorations (21,22).

A typical choice for retainer design of posterior RBFPDs consists of two wraparound 180˚ lingual wings and two rests adjacent to the edentulous space (23). A number of previous studies and literature reviews (5,7,23-25) have introduced modified retainer designs, including an inlay retainer, a retainer with mesiodistal double rests on one abutment, C- or D-shaped retainers and dental bands designated O-shaped retainers. Nevertheless, there are no standard posterior porcelain-fused-to-metal (PFM) RBFPD designs currently available for clinical use.

The aim of the present study was to investigate the effect of different surface treatments, namely, airborne particle abrasion and primer coatings, on the adhesive ability of Pd-Ag, and to explore whether treatment with a silica coating + silane could provide an equal or improved outcome in terms of increased bond strength compared to treatment with an alloy primer. The present study also compared the retention of posterior Pd-Ag RBFPDs with that of different retainer designs to identify appropriate retainer designs for posterior Pd-Ag RBFPDs and support their clinical application.

Materials and methods

Effect of airborne particle abrasion on the shear bond strength (SBS) of Pd-Ag and enamel. In total, 40 recently extracted maxillary central incisors were collected from the West China Hospital of Stomatology (Chengdu, China). A total of 140 patients, including 76 males and 64 females (11-71 years), at all stages were recruited from West China Hospital of Stomatology. The patients were recited between May 2014 and September 2014, and September 2016 and December 2016. Ethical approval was granted by the Institutional Review Board, West China Hospital of Stomatology, and written informed consent was obtained from all study participants. The incisors were carefully cleaned and divided into four groups (n=10) by block randomization according to the shape and area of the labial surface. The labial surfaces were ground within the enamel on a polishing machine (Struers ApS Ballerup, Denmark) with 600 grit silica carbide waterproof abrasive paper (Eagle Industry Sales Co. Ltd., Shanghai, China). This procedure was performed to mimic clinical tooth preparation with a yellow-labeled diamond bur. The shape of each ground enamel plane was made as round as possible with a diameter ≥6.0 mm. Subsequently, the roots of the teeth were embedded in cuboid-shaped, heat-cured denture base resin (Shanghai Dajin Logistics Co., Ltd., Shanghai, China) and the perpendicularity of each labial enamel plane to the horizon was ensured.

In total, 40 Pd-Ag (W-1; Ivoclar Vivadent AG, Schaan, Liechtenstein; Table I) discs were cast using a standard model (diameter, 5.0 mm; thickness, 2.5 mm). The diameter was measured using digital calipers (Chengdu Chengliang Tools Group Co., Ltd., Chengdu, China) and the area (S) of the disc was calculated using $S=\pi^{*}$ (diameter/2)^2. Furthermore, the bonding surface of each disc was ground sequentially with 400, 600, 800, 1,200, 1,500 and 2,000 grit abrasive paper. The discs were randomly distributed into 4 groups (n=10) according to the following sandblasting particle sizes: Group a, control, 2,000 grit without sandblasting; group b, 50 μm; group c, 110 μm; and group d, 250 μm. The last three groups of discs were subjected to Al_2O_3 sandblasting for 10 sec at a pressure of 0.28 MPa and a distance of 10 mm using an abrasive blasting machine (Easyblast; BEGO GmbH & Co., KG, Bremen, Germany). Each Pd-Ag disc was then observed under a stereomicroscope (Inspect; FEI; Thermo Fisher Scientific, Inc., Waltham, MA, USA) at x500 magnification to observe the surface morphology following sandblasting with different Al_2O_3 particle sizes (Fig. 1). Following ultrasonic cleaning in a water bath (Ultrasonic Cleaner; Hangzhou Baobo Ultrasonic Technology Co., Ltd., Hangzhou, China) three times for 2 min each, all Pd-Ag discs were cemented onto the prepared enamel planes with Panavia F 2.0 (Kuraray Co., Ltd., Tokyo, Japan; Table I).

Prior to cementation, each polished labial enamel plane was cleaned with an ethyl alcohol swab and dried with an oil-free air sprayer. The enamel plane was then etched with 35% phosphoric acid (Heraeus Gluma Gmbh, Hanau, Germany) for 40 sec, cleaned with distilled water spray for ≥1 min and dried with clean air. The enamel surface was subsequently treated with a mixture of primers one and two provided with Panavia F 2.0 according to the manufacturer's protocol. Following treatment of the surface of the enamel, the Pd-Ag disc was cemented onto the enamel with Panavia F 2.0 according to the manufacturer's protocol. Excess mixed paste was subsequently removed and the oxygen inhibition agent provided with Panavia was coated along the adhesive margin. The adhesive was then cured with an LED curing light (Foshan Duoyimei Medical Instrument Co., Ltd., Foshan, China) four times for 60 sec each from four directions at 90˚ intervals. The wavelength and working power of the curing light was 450-480 nm and 1,000 mw/cm^2, respectively.

Following cementation, all specimens were subjected to 5,000 rounds of thermal cycling (5-55˚C, 30 sec in each water bath), which were performed to simulate the aging effect of luting cement. All specimens were dislodged using a universal testing machine (Instron 5565; Instron, Norwood, MA, USA; Fig. 2) with a wedge-shaped loading component parallel to the adhesion surface and a loading speed of 0.5 mm/min. The loading stopped automatically when the continuously ascending load-displacement curve suddenly descended. The peak value prior to recording this descent was measured as the dislodging force (F). Furthermore, the SBS was calculated according to the formula SBS=F/S, and the SBS values were recorded in MPa.

Table I. Composition and manufacturer of applied materials.

Name	Batch	Composition	Manufacturer
Panavia F 2.0	*00256A 00034A, 00323A 00196A*	BPEDMA, MDP, DMA, and sodium fluoride	Kuraray Co., Ltd., Tokyo, Japan
W-1 Pd-Ag alloy	-	Pd (53.3%), Ag (37.7%), Sn (8.5%), others (0.5%)	Ivoclar Vivadent AG, Schaan, Liechtenstein
Rx	121120	SiH_4	Pulpdent Corporation, Watertown, MA, USA
Alloy primer	00205A	VBATDT, MDP	Kuraray Co., Ltd., Tokyo, Japan
Silica (Rocatec Soft)	-	30-μm silica-coated Al_2O_3 particles	3M ESPE AG, Seefeld, Germany

BPEDMA, bisphenol-A-polyethoxydimethacrylate; DMA, aliphatic dimethacrylate; MDP, 10-methacryloyloxy-decyl-dihydrogenphosphate; VBATDT: 6-(4-Vinylbenzyl-N-propyl) amino-1, 3, 5-triazine-2, 4-dithione.

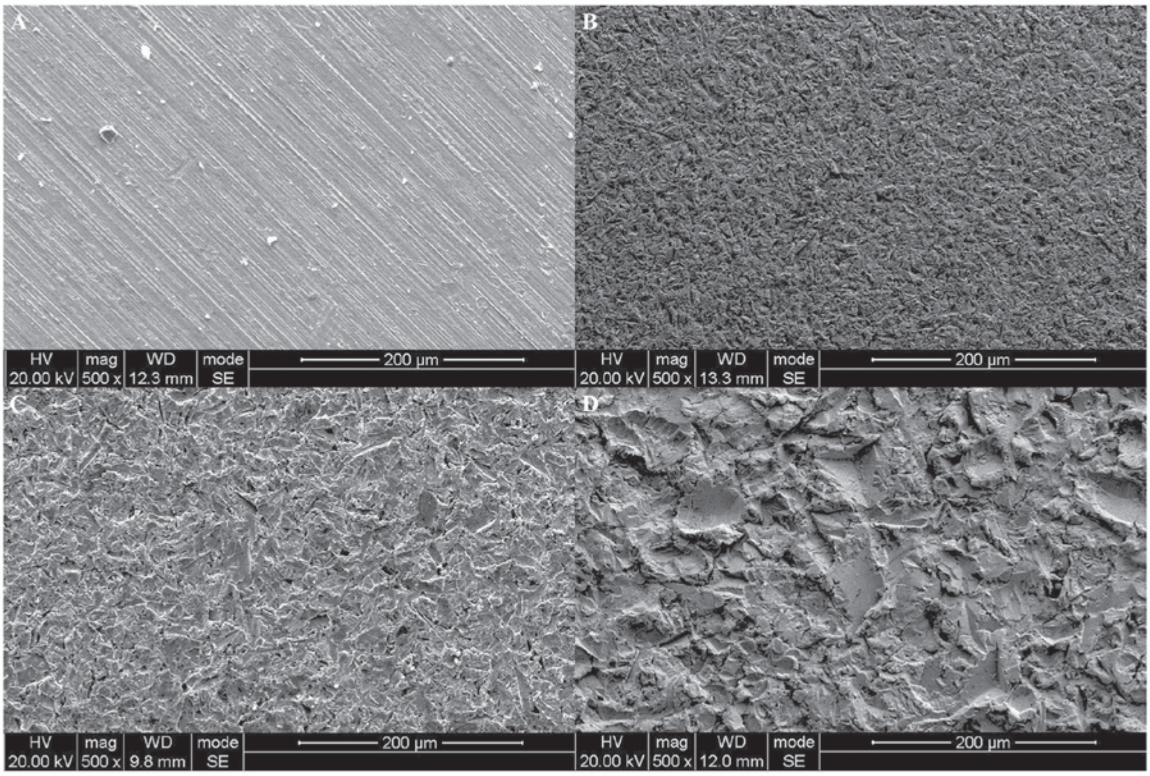

Figure 1. (A) Surface morphology following 2000 grit polishing. (B) Surface morphology following 50-μm Al_2O_3 particle abrasion. (C) Surface morphology following 110-μm Al_2O_3 particle abrasion and (D) surface morphology following 250-μm Al_2O_3 particle abrasion.

Effect of primer treatment on Pd-Ag disc SBS. In total, 50 additional central incisors were collected, and the tooth preparation and Pd-Ag disc fabrication was the same as described above. All 50 discs were abraded with airborne Al_2O_3 particles (250 μm, the most effective particle size selected in the previous experiment). Subsequently, the discs were divided into five groups (n=10) and treated with different primers: Group e, sandblasting only, as a control; group f, silane only (Rx; Pulpdent Corporation, Watertown, MA, USA) according to the manufacturer's protocol; group g, noble alloy primer only (Kuraray Co., Ltd., Tokyo, Japan) according to the manufacturer's protocol; group h, silica coating (Rocatec Soft, 3M ESPE AG, Seefeld, Germany) + silane; and group I, silica coating + noble alloy primer (Table I). For the silica coating, Rocatec silica-modified Al_2O_3 particles were sprayed onto the sandblasted discs at a pressure of 0.2 MPa from a distance of 10 mm and for a duration of 2 sec (Fig. 3). Subsequently, the same cleaning, tooth etching, cementation, thermal cycling, SBS testing and statistical analysis as described above were applied.

Analysis and assignment of failure mode. In the previous experiments, following SBS testing, gold-coated Pd-Ag fracture surfaces were examined by scanning electron microscopy (magnification, x50). The failure mode was classified as one of the four types listed below and assigned the following values (26-28): Type 1, adhesive mode where the complete alloy surface was visible and was assigned a value of 0; type 2, mixed mode where the alloy surface and a (partial) cement cover were visible and was assigned a value of 1; type 3, mixed mode where the alloy surface and a (partial) cement cover were visible, along with a cohesive fracture within the cement layer and was assigned a value of 2; and type 4, cohesive mode where almost the entire fracture surface was covered with cement and was assigned a value of 3.

The failure mode distribution was recorded, and the mean score of each group was calculated.

In vitro study of different Pd-Ag PFM RBFPD retainer designs. A total of 40 missing second premolar models were established with recently extracted maxillary premolars and molars collected at the West China School and Hospital of Stomatology. Subsequently, 40 Pd-Ag PFM 3-unit fixed-fixed RBFPDs were fabricated to restore the missing second premolars using four retention form types (n=10). The retainer designs are illustrated in Fig. 4, as follows: Group I, a premolar lingual wing with an occlusal bar combined with a molar lingual wing with double rests (MDR); group II, a lingual wing with an occlusal bar for both abutments (OBB); group III, a premolar lingual wing with an occlusal bar combined with a molar dental band (MDB) and group IV (control), a lingual wing with a single rest adjacent to the edentulous space (SRB), which was considered a typical design in a recent study (23). Prior to embedding, two-layered wet medical tape was wrapped around the abutment root as an artificial periodontal membrane. The depth of the rest seat and belt groove was 0.8-1.0 mm, the wraparound of the lingual wing covered ≥180˚, the wing width was 3-5 mm and the wing thickness was 0.8 mm.

The Pd-Ag PFM RBFPDs were pretreated based on the results from previous parts of the present study. Next, they were cemented as described above with Panavia F 2.0. Subsequently, all specimens were subjected to 5,000 rounds of 5-55˚C thermal cycling and 1.2 million rounds of mechanical loading with 50 N at a frequency of 2 Hz perpendicular to the pontic occlusal surface at the central fossa. The loading stylus was fabricated from an Ni-Cr alloy, and the descending speed of the stylus was 5.6 cm/sec. Furthermore, the loading process proceeded under wet conditions. The 1.2 million rounds of mechanical loading were used to simulate the effect of normal masticatory movement. Following loading, a residual retention (RR) test was performed on all the surviving dentures using a universal testing machine at a speed of 1 mm/min. The whole specimen and resin base were fixed on the lower part of the universal testing machine and a hook was fixed on the upper part located exactly below the pontic of the RBFPD. When the continuously ascending load-displacement curve suddenly descended, the peak value was recorded in N as the RR force. The retainers that debonded from each RBFPD during the peak RR force were recorded and counted. The methods employed in all parts of the present study were designed according to the results of previous studies (5,29-32).

Statistical analysis. The SBS results in airborne particle abrasion study and primer treatment study, and results in retainer designs study are presented as mean ± standard deviation (n=10). Data was analyzed using SPSS (version 19; IBM Corp., Armonk, NY, USA) using one-way analysis of variance and the Student-Newman-Keuls q-test at α=0.05. The results of failure mode analysis are presented as frequency of occurrence. Data was analyzed using Fisher's exact probability test at α=0.05. The mean score of each group is presented as mean ± standard deviation (n=10). P<0.05 was considered to indicate a statistically significant difference.

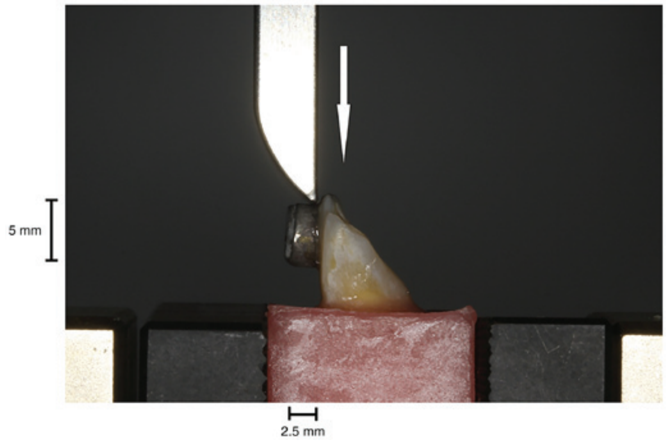

Figure 2. During the shear bond strength test, the wedge-shaped loading stylus was parallel and close to the bonding interface.

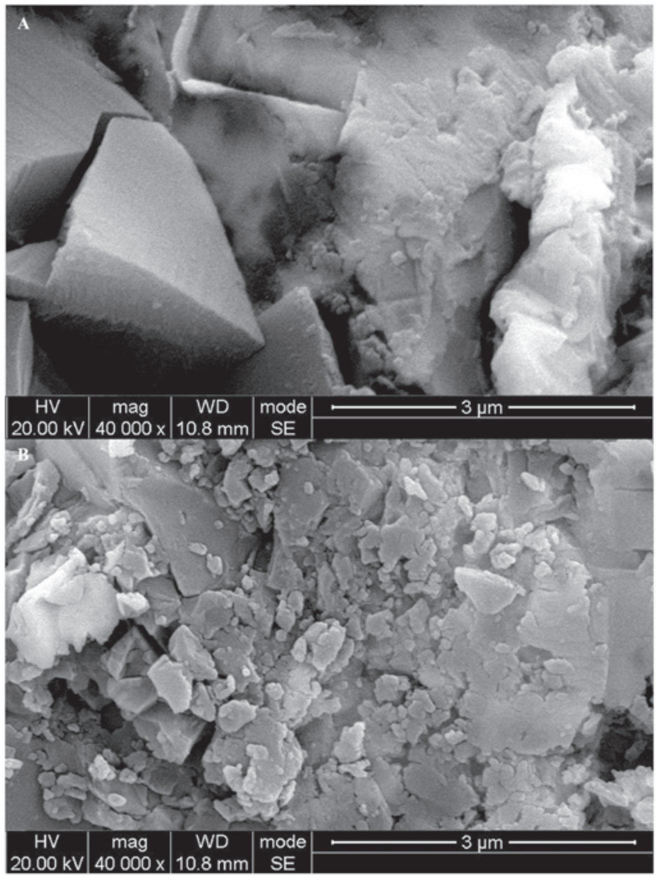

Figure 3. (A) Scanning electron microscopy images of the palladium-silver alloy disc surface following 250-μm Al_2O_3 particle abrasion. (B) Disc surface following 250-μm Al_2O_3 particle abrasion and silica coating.

Results

The SBS results of airborne particle abrasion study. The mean values and standard deviations of the four experimental groups in the different airborne particle abrasion study are

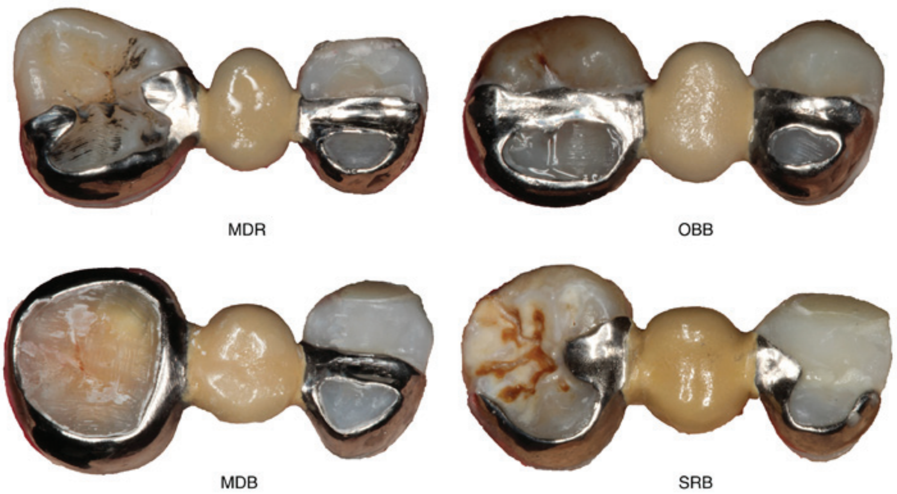

Figure 4. MDR depicts the form of group I, with a premolar bar combined with molar double rests. OBB depicts the form of group II, with double occlusal bars. MDB reveals the form of group III, with a premolar occlusal bar combined with a molar dental band. SRB reveals a typical resin-bonded fixed partial dentures design, used in group IV as a control, with a single rest on each abutment combined with 180˚ lingual flanges. MDR, premolar lingual wing with occlusal bar combined with molar lingual wing with double rests; OBB, lingual wing with occlusal bar for both abutments; MDB, premolar lingual wing with occlusal bar combined with molar dental band; SRB, lingual wing with single rest adjacent to edentulous space (control).

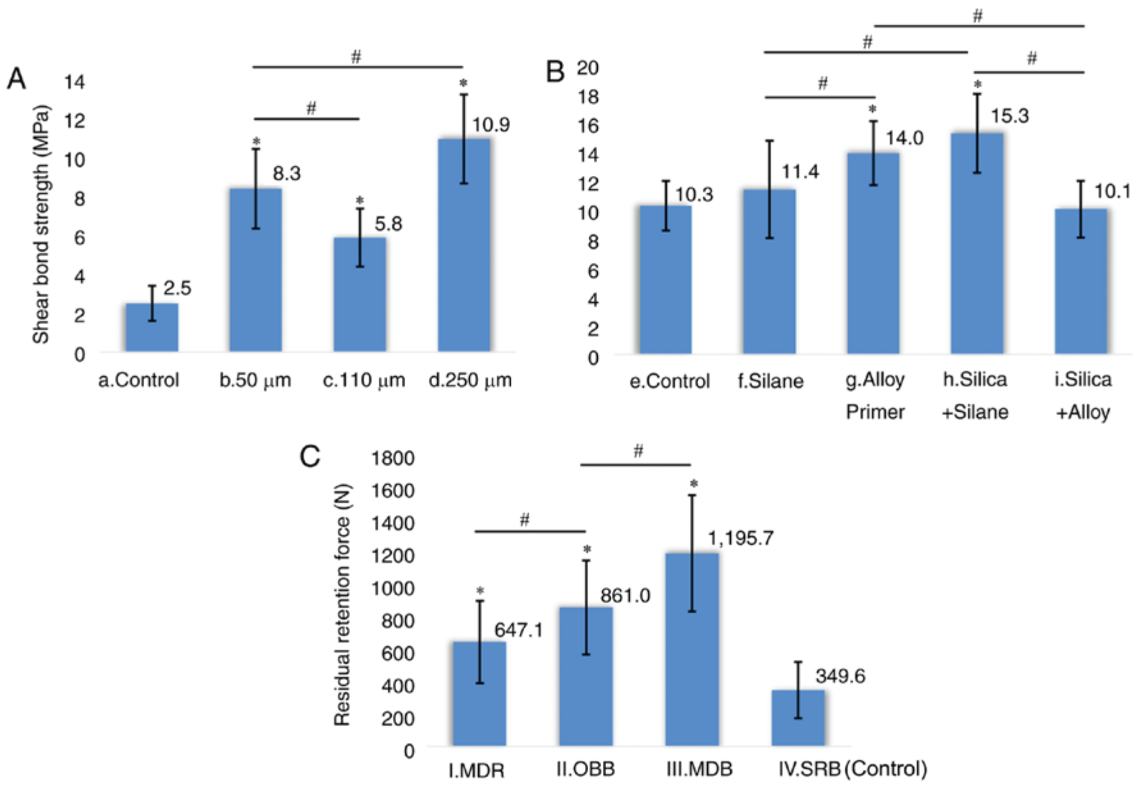

Figure 5. (A) Shear bond strength results from the airborne particle abrasion study, (B) the primer treatment study and (C) the residual retention test results from different retainer designs study. Data are presented as the mean ± standard deviation. *P<0.05 vs. control, #P<0.05. MDR, premolar lingual wing with occlusal bar combined with molar lingual wing with double rests; OBB, lingual wing with occlusal bar for both abutments; MDB, premolar lingual wing with occlusal bar combined with molar dental band; SRB, lingual wing with single rest adjacent to edentulous space (control).

summarized in Fig. 5. As the highest SBS was detected in the group treated with abrasion by 250-μm particles (P<0.05; Fig. 5A), 250-μm Al_2O_3 particles were selected for further experiments.

The SBS results of primer treatment study. The results from the primer treatment study are depicted in Fig. 5B. The mean SBS values of groups g and h were significantly higher than those of the control group and groups f and i (P<0.05) but there was no significant difference between groups g and h. As depicted in Fig. 3, the surface morphology of the alloy sandblasted by 250-μm Al_2O_3 particles changed following coating with silica as a certain amount of silica remained on the alloy surface. The mean values of groups f and i were not

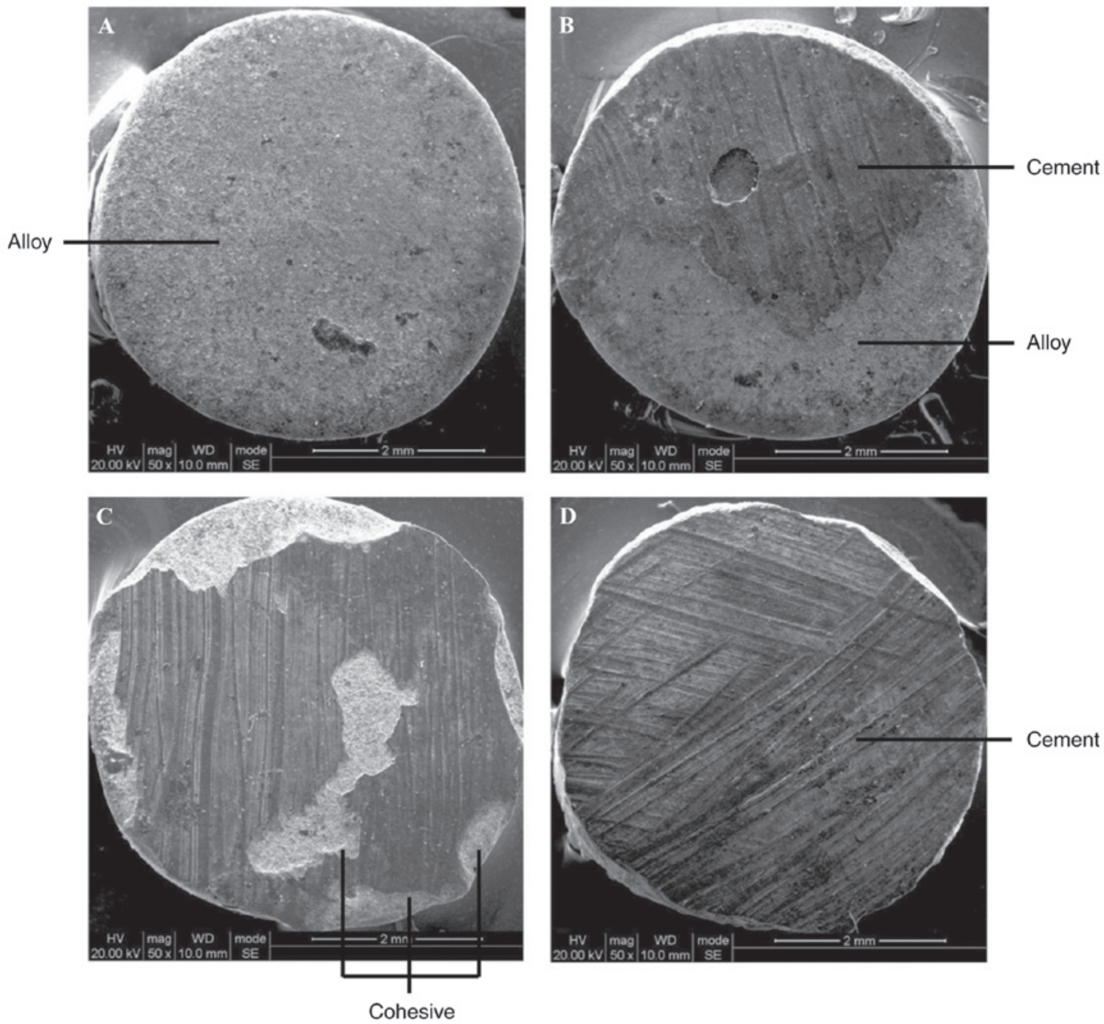

Figure 6. Scanning electron microscopy images (magnification, x50) of the different failure types. (A) Adhesive mode, complete alloy surface was visible; (B) mixed mode, the alloy surface and a (partial) cement cover were visible; (C) mixed mode, the alloy surface and a (partial) cement cover were visible, along with a cohesive fracture within the cement layer and (D) cohesive mode, almost the entire fracture surface was covered with cement.

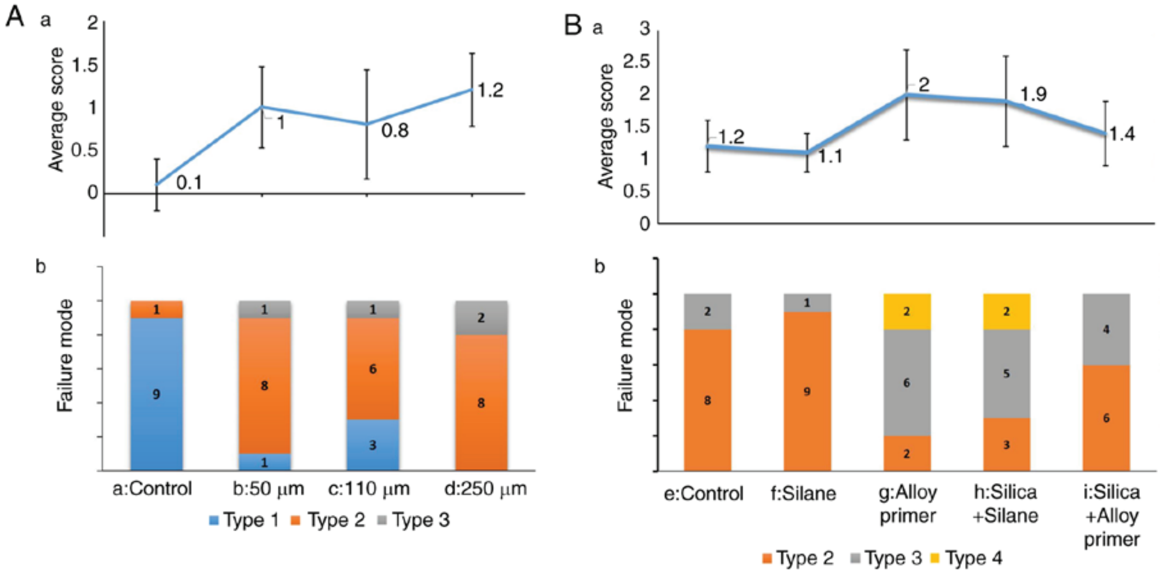

Figure 7. (Aa) Mean score of each group in the airborne particle abrasion study. The highest score was 1.2 in group d (250-μm Al_2O_3 particle abrasion). (Ab) Failure mode distribution in the airborne particle abrasion study; the distribution was significantly different among the four groups (P<0.05). (Ba) Mean score of each group in the primer treatment study. (Bb) Failure mode distribution in the primer treatment study; the distribution was significantly different among the four groups (P<0.05). Failure mode type 4 occurred in groups g and h. The mean score in these two groups was 2.0 and 1.9, respectively. Data are presented as the mean ± standard deviation (n=10/group).

Table II. Sum of the debonded retainers in each group during the residual retention test.

Group	Premolar retainer (n)	Molar retainer (n)	Sum (n)
MDR (I)	2	7	9
OBB (II)	7	3	10
MDB (III)	10	0	10
SRB (IV)	9	0	9

Sum of debonded retainers when the loading-displacement curve first dropped during the residual retention test on the universal testing machine is presented for each group. MDR, premolar lingual wing with occlusal bar combined with molar lingual wing with double rests; OBB, lingual wing with occlusal bar for both abutments; MDB, premolar lingual wing with occlusal bar combined with molar dental band; SRB, lingual wing with single rest adjacent to edentulous space (control).

significantly different compared with the control. According to these results, airborne particle abrasion with 250-μm Al_2O_3 particles combined with the noble alloy primer coating was selected to treat the Pd-Ag RBFPDs.

The results of analysis and assignment of failure mode. The four failure modes of the Pd-Ag adhesive surface are presented in Fig. 6, and the failure mode distribution of groups a-i is presented in Fig. 7. In the airborne particle abrasion study, failure mode types 1, 2 and 3 occurred. In addition, the failure modes were significantly different between all groups (P<0.05). The trend of the mean scores in groups a-d was in accordance with that of the corresponding SBS values. The highest score was 1.2 in group d. Failure mode type 2, 3 and 4 occurred in groups of the primer treatment study, and the mode distribution varied significantly among the five groups (P<0.05). The trend of the mean scores in groups e-i was also similar to that of the corresponding SBS values. The highest scores were 2.0 in group g and 1.9 in group h. In addition, the type 4 failure mode occurred only in these two groups.

The results of different retainer designs study. The RBFPDs in groups II and III (the OBB and MDB designs, respectively) were successful following water aging and mechanical loading. However, 1 prosthesis in group IV debonded during the mechanical loading cycles. The debonded prosthesis was intact and could be rebonded onto the edentulous model following appropriate sandblasting and cleaning. Additionally, due to molar abutment fracture, one restoration in group I failed and was damaged. The RR testing results (Fig. 5C) revealed significant differences between the mean values of the four designs (P<0.05). The MDB design retained the highest RR (P<0.05), the mean value of the OBB design was higher than that of the MDR design (P<0.05) and the SRB design had the lowest RR (P<0.05). Whether the premolar or molar retainers debonded during the peak RR force is summarized in Table II. In the MDR group, 2 premolar retainers and 7 molar retainers debonded. In the OBB group, 7 premolar retainers and 3 molar retainers debonded and in the other two groups, all premolar retainers debonded at the ultimate strength point. According to Fisher's exact probability test, the debonding results among these four designs were significantly different (P<0.05).

Discussion

Pd-Ag is able to be cast into RBFPDs due to its acceptable adhesive strength (14), which is derived from the surface oxide layer. According to the preliminary data from the fabrication laboratory of the West China School and Hospital of Stomatology, Pd-Ag-based metal-ceramic FDPs account for >50% of the demand among all metal-ceramic dentures (data not shown). Therefore, investigating Pd-Ag RBFPDs has clinical importance.

Although previous studies have investigated the bonding strength of noble alloys, few *in vitro* studies have assessed the interfacial bonding strength between Pd-Ag and enamel (18,20,26). RBFPDs require enamel bonding and minimally invasive preparation. Therefore, the interfacial bonding strength between this alloy and enamel was examined in the present study, and the suitability of different retainer designs for clinical application was also investigated.

In a recent 3D finite element study, Lin *et al* (5) revealed that D- and O-shaped retainers were more structurally rigid than the traditional C-shaped retainer. However, using the O-shaped retainer for premolar comes at a higher biological cost and carries a high risk of poor aesthetic. Therefore, a D-shaped retainer was designed for premolar abutments and three different retainer designs for molars. The purpose of the present study was not only to compare the retention of the different designs but also to identify the posterior Pd-Ag FPM RBFPD that is aesthetically pleasing, requires minimally invasive preparation and provides adequate retention.

As the SBS values of the three abrasion groups were higher than that of the control, the Al_2O_3 particle abrasion was demonstrated to enhance the bonding propensity of Pd-Ag. Due to different experimental conditions, there has been a lack of unified abrasion standards (17,18,33). Mukai *et al* (34) previously observed no significant difference in the bond strength of a composite resin to Ni-Cr alloy when 37 and 250-μm Al_2O_3 particles were used. Barclay *et al* (17) identified similar results when four different grit sizes were used. However, Petridis *et al* (18) revealed higher SBS values for resin to a noble alloy following sandblasting with 50-μm Al_2O_3 particles compared to 250-μm particles. By contrast, Watanabe *et al* (35) and Papadopoulos *et al* (33) observed improved results when commercially pure Ti was abraded with 250-μm particles compared with 50-μm particles. Under the present abrasion parameters, the results indicated that sandblasting Pd-Ag discs with 250-μm Al_2O_3 particles yielded an improved result in promoting bonding strength. This outcome may have occurred due to the fact that the 250-μm-diameter particles caused the formation of more intricate micro-mechanical locking structures on the surface. Additionally, larger particles with higher kinetic energy may create deeper micro-grooves in the surface, which may result in the formation of stronger resin tags. However, the 110-μm particles revealed the lowest bonding strength, inferior to that of the 250 and 50-μm particles. A previous study have not reported this observation (36). A possible explanation is that the 50-μm particles increased the surface wettability and that this effect was more notable than that of the mechanical locking structure formation caused by the 110-μm particles, but less than that caused by the 250-μm particles. However, further studies are necessary to confirm this hypothesis.

These results revealed that the alloy primer was able to enhance the bonding ability of abraded Pd-Ag. Similar behavior has been observed in a number of previous studies (31,37). However, Abreu *et al* (38) observed that neither metal type nor surface pretreatment affected bond strength. The alloy primer used in the present study contained 6-(4-vinylbenzyl-N-propyl) amino-1,3,5-triazine-2,4-dithione (VBATDT) and MDP. The sulfur atom in VBATDT creates a chemical bond with palladium atoms, and the -C-C- on the opposite end chemically combines with resin molecules.

In addition, under the conditions of the present study, the highest SBS value of the primer-treated discs to enamel was 15.3±2.7 MPa. Compared with the results of previous studies (20,39), the mean values were not notably high. A possible reason for this may be due to the diameter of the disc being only 5 mm; therefore, the influence of 5,000 thermal cycles was more significant on the bonding interface and alloy disc. Another reason may be that when preparing the enamel plane, obtaining a 6-mm-diameter plane required the removal of the superficial enamel (40). Although the mean SBS values were lower than those of previous studies, the significant differences among the different surface treatments and the different failure modes among the groups still have relevance for clinical practice. The application of an alloy primer coating (31,37) and a silica coating with a silane primer may increase the bonding strength of Pd-Ag. Generally, silica coatings are finished in a laboratory, whereas alloy primer coatings and silane coatings may be finished by dentists in a clinic. However, the present study failed to show that using a silica coating combined with silane was better than using only an alloy primer. Therefore, these findings suggest that an alloy primer coating should be used, particularly due to its ease of use.

As for the RBFPD retainer design, aside from adequate retention and mechanical strength, the retainer must also be as minimally invasive as possible. However, aesthetics should not be ignored. The mean mesiodistal dimension of Chinese first premolars is 7.1-7.2 mm, and the lingual occlusal-gingival height is less than that of the buccal side (41). Occlusal bars may help to resist the axial dislodging force. In the clinic, this type of retainer is particularly suited for abutments with an occlusal pit and fissure caries. Compared with the early typical RBFPD design (the control), double rests for molar retainers increase the bonding area and the sturdiness of the entire framework. Although the occlusal bar further expands the bonding area and sturdiness, when compared with inlay retainers (25) or dental band retainers, the occlusal bar is less invasive. The dental band retainer supports the largest bonding area but it is also the most invasive RBFPD design. Additionally, the buccal part of the band may be visible when speaking or smiling, thereby affecting the aesthetics of RBFPDs.

A number of limitations should be taken into consideration in the present study. The clinical significance of the airborne particle abrasion study was limited as only one dental alloy was studied, and the results were different from those of a number of previous studies, in which 50-μm Al_2O_3 particles have been revealed to be better abrasion particles for other dental materials (18,42). Additionally, posterior cantilevered RBFPDs or any ceramic RBFPDs were not investigated in the present study. In a number of previous original and retrospective studies (43,44), two-unit cantilevered RBFPDs were reported to have an improved survival rate compared with their three-unit counterparts. Further studies are necessary to compare these two designs in the posterior area by the same method used in the present study.

In addition, all ceramic, particularly zirconia-based, RBFPDs should be investigated in the future. Zirconia not only helps to solve the aesthetic drawbacks of PFM RBFPDs but also allows a more conservative tooth preparation due to its adequate mechanical properties (45).

Under the limitations of the present simulated restoration, the four designed Pd-Ag PFM RBFPDs exhibited an acceptable survival rate (mimicking 5-year outcomes) following mechanical loading. The three modified designs performed better than the control. Furthermore, dental band retainers were able to offer the highest retention by providing the greatest bonding area and a 360˚ wraparound form. The OBB and MDR designs also supported higher retention than the control. Considering minimally invasive tooth preparation and aesthetic design, Pd-Ag PFM MDR RBFPDs and OBB RBFPDs are the recommended alternatives for restoring missing maxillary second premolars or first molars in the context of a narrow edentulous space.

In conclusion, within the limitations of the present *in vitro* study, 250-μm Al_2O_3 particle abrasion with the use of a silica coating combined with silane or noble alloy primer alone are effective means of increasing the bonding properties of dental Pd-Ag. Furthermore, posterior Pd-Ag RBFPDs provide acceptable outcomes for as long as 5 years. An occlusal bar with a lingual wing and double rests with a lingual wing are recommended retainer designs for clinical practice.

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