Clinical performance of two different adhesive strategies for metal-ceramic cracks repairing and related in vitro study

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To evaluate the bonding reliability of a universal adhesive compared to a commercial ceramic repair system for metal-ceramic cracks. In vitro part: sixty specimens with porcelain, metal and porcelain-metal substrate were fabricated. Half specimens were bonded by Singlebond Universal adhesive and Filtek Z350 resin composite. The other were processed by Ceramic Repair N. Shear bond strength was tested. In vivo part: forty patients with sixty ceramic fractured porcelain-fused-metal restorations were involved. Half were repaired by Singlebond Universal and Filtek Z350. The other were restored by Ceramic Repair N. The mean observation period was 65 weeks. Results showed the bond strength ranged from 13.97 MPa to 15.85 MPa using two different repair system on different substrate with no statistical difference. There was no statistical difference between the two adhesive system in survival rate according to Kaplan-Meier analysis. The universal adhesive had a similar repair performance compared to commercial ceramic repair system.

Keywords: Ceramic crack, Repair, Universal adhesive, Bond strength

INTRODUCTION

Despite the development and popularity of all ceramic and zirconia, metal-ceramic restorations are still a good alternative for oral rehabilitation1. Metal-ceramic restorations combines the cosmetic appearance of porcelain and the intensity properties of metal alloys in one single prosthesis. Although the technology of porcelain fused to the metal substrate have highly improved, failures still happen at times2. The most common failure is porcelain crack and its prevalence is about 2.6%3 in a cumulative five-year. Due to the inadequate occlusal adjustment, parafunctional habits, inadequate tooth preparation, improper design, porcelain-fused-to-metal (PFM) restorations developed porcelain cracks4,5. Though these cracks do not imply completely fused-to-metal (PFM) restorations developed porcelain inadequately tooth preparation, improper design, porcelain-inadequate occlusal adjustment, parafunctional habits, or remaking a new one seems inevitable3,7. However, intraoral repair of the restoration with composite resin 12,13 is reasonable3.8,11. As a consequence, the direct intraoral repair of the cracked ceramic with composite resin is reasonable3,8,11. Several intraoral porcelain repair systems are now commercialized and their effectiveness are satisfactory12,13. Some porcelain repair system such as Ceramic Repair® Kit (Ceramic Repair N, Ivoclar Vivadent, Schaan, Liechtenstein), Cimara® Repair Kit (Voco, Cuxhaven, Germany), and ClearfilTM Repair Kit (Kuraray Medical, Tokyo, Japan) are commonly indicated in clinical practice. A commercial repair kit often consists of an ceramic primer, a bonding agent and composite resin including opaque resin and conventional resin. The repair systems have defined sequence of application but the procedures for clinicians are too complex and time-consuming.

One of the most recent novelties in adhesive dentistry was the introduction of universal adhesives. They consist of versatile elements in a single bottle14 and are recommended to bond not only to enamel, dentin, resin, but also ceramic and metal without compromising bonding effectiveness8,15. The universal adhesives incorporate phosphate monomers (10-methacryloyloxydecyl dihydrogen phosphate; MDP) and silanized particles in their formulation16, which subtracts the step of silanization before bonding and thus makes the usage of these adhesives simple and efficient8,14. Due to the fusion of functional ingredients, the universal adhesives replace multiple clinical procedures which makes it more friendly.

Although several researches focused on the bond strength of commercial ceramic repair systems, little literatures have studied the effect of universal adhesives repairing ceramic cracked restoration or compared the efficiency of a commercial repair kit and a universal adhesive, especially absence in vivo study. Thus, the aim of this study was to evaluate the bond strength of the all-in-one and one-step universal adhesive to a composite resin repairing a porcelain cracked metal-ceramic restoration in comparison to a commercial ceramic repair kit both in vitro and in vivo. The null hypotheses were that (1) The bonding strength of universal adhesive
would not be lower than conventional ceramic repair system \textit{in vitro} and (2) The clinical performance of universal adhesive would not demonstrate worse than conventional ceramic repair system \textit{in vivo}.

**MATERIALS AND METHODS**

The materials used in this study were shown in Table 1 and the usage were in accordance with the manufacturer’s directions. The universal adhesive used was Singlebond Universal (S) (3M ESPE, St. Paul, MN, USA). The specific intraoral ceramic repair system used was Ceramic Repair Kit (C) (Ivoclar Vivadent). During the course of the study, a light curing unit (Spectrum 800 Curing Unit, Dentsply DeTrey, Konstanz, Germany) was used and set at a light irradiance of 600 mW/cm².

**Part I: Evaluation of bonding strength of the two repair systems \textit{in vitro}**

1. Specimen preparation

Sixty plates (10×10 mm, 3 mm thickness) with three different substrates and two adhesive systems composed six subgroups. Among which, the first twenty plates were fabricated from cobalt-chromium base metal alloy (Bego, Bremen, Germany) and the adhesive surface designed as entire metal (M), imitating the porcelain crack with substantial metal exposure (Fig. 1, the first one from the left). The second twenty plates were fabricated from feldspathic porcelain (Shofu, Kyoto, Japan) fused to cobalt-chromium base metal alloy (porcelain 1.5 mm thickness, metal 1.5 mm thickness) and the adhesive surface designed as entire porcelain (P), imitating the porcelain crack involving only the porcelain body (Fig. 1, the second one). The last twenty plates were fabricated from feldspathic porcelain fused to cobalt-chromium base metal alloy and the adhesive surface designed as half porcelain and half metal (H), imitating the porcelain crack associated with the exposure of metal and porcelain (Fig. 1, the third one from the left). The specimens of each substrate were randomly assigned into two groups as follows (n=10): SM (Singlebond Universal adhesive+metal substrate); CM (Ceramic Repair Kit+metal substrate); SP (Singlebond Universal adhesive+porcelain substrate); CP (Ceramic Repair Kit+porcelain substrate); SH (Singlebond Universal adhesive+half metal half porcelain substrate); CH (Ceramic Repair Kit+half metal half porcelain substrate), among which SM, SP and SH were experimental groups while CM, CP and CH were control groups.

2. Adhesion

All specimens were washed for 3 min with 75% ethanol and roughened by a coarse diamond bur with intermittent strokes for 20 s till the adhesive surface shown evident scratches using water irrigation. Then they were washed with air and water jet, and dried for 30 s. The adhesion area was limited using a double sided tape (Scotch® 3M) with previously drilled by a perforator (diameter 5 mm). In the experimental groups (SM, SP, SH), Singlebond Universal adhesive was applied to the adhesive surface with rubbing action for 20 s and then medium air pressure was applied to surface for 5 s according to manufacturer’s instruction. Then they were used light to cure for 20 s. Tygon tubes with 6 mm internal diameter and 3 mm height were installed on the exposed area to build a cylinder of composite resin (Filtek Z350 XT, 3M ESPE). The resin composite was placed into the tube with a condensing instrument and light cured for 20 s for each 1 mm layer. If the adhesive surface had metal exposed, opaque resin (Filtek Z350 XT, 3M ESPE, shade WD) was applied to cover the metal. In the control groups (CM, CP, CH), the first step was to use a brush applying Monobond N to the adhesive surface and kept 60 s plus air drying for reaction.

**Table 1** The material used in this study

| Adhesive                  | Material description | Manufacturer                          | Main components                                                                 |
|---------------------------|----------------------|----------------------------------------|---------------------------------------------------------------------------------|
| Singlebond Universal      | Universal adhesive   | 3M ESPE Dental, St. Paul, MN, USA       | MDP phosphate monomer, HEMA, 3M ESPE, dimethacrylate resins, Vitreobond copolymer, filler, ethanol, water, initiators, silane |
|                           |                      |                                        | Monobond-N: 3-methacryloxypropyl-trimethoxysilane                               |
|                           |                      |                                        | Heliobond (light-curing bonding agent): Bis-GMA and triethylene                  |
|                           |                      |                                        | glycol dimethacrylate, catalysts and stabilizers                                |
| Ceramic Repair Kit        | Intraoral Ceramics   | Ivoclar Vivadent, Schaan, Liechtenstein | IPS Empress Direct Opaque (opaque): Bis-GMA, urethane                          |
|                           |                      |                                        | dimethacrylate, and triethylene glycol dimethacrylate; barium glass, ytterbium trifluoride, Ba-Al fluorosilicate glass, and spheroid mixed oxide; catalysts, stabilizers, and pigments |
|                           |                      |                                        | Tetric N-Ceram (light-curing nano-hybrid composite): dimethacrylates; Filler; catalysts, stabilizers and pigments |
Subsequently, a thin layer of Heliobond was applied. The excess adhesive was removed by compressed air. Then light cured for 20 s. The above tygon tubes were placed on the processed surface. If the substrate exposed metal, IPS Empress Direct Opaque was applied to the prepared metal surface with the thickness of 0.5 mm maximum and light-cure for 20 s. Tetric N-Ceram was applied in increments of maximum 2 mm and adapted into the tube with a suitable instrument. Each layer was light cured individually for 20 s. All specimen were stored in distilled water at 37°C for 24. Tygon tubes were then removed using scalpel blades #12. After that, all specimen were embedded in an autopolymerizing acrylic resin as a base using a polyethylene mold (15×15×20 mm), leaving the test surface uncovered. The shear bond strength test (SBS) was executed using a universal mechanical testing machine (AG-X Plus, Shimadzu, Kyoto, Japan) with a 50 N load and a 0.5 mm/min unit crosshead speed. A chisel-shaped metal indenter was prepared to apply a parallel load to the resin composite cylinder close to the flat ground specimen surface. The peak loads at failure were recorded. All test were performed close to the flat ground specimen surface. The peak load, σ, was calculated using the equation σ=F/A, where F corresponded to the peak load at the separated failure (N) and A corresponded to the adhesive area determined by the equation πr² (mm²). The adhesive area in this study was 19.625 mm².

3. Failure classification
After SBS, the adhesive sites of the specimens and resin composite cylinders were examined under a stereomicroscope at 500× magnification (AG-X Plus, Shimadzu) in an attempt to identify the bond failure mode. Failures were classified as follows: adhesive, when separation occurred between the two interfaces (ceramic/metal and resin); cohesive, when separation occurred within a single interface, leaving a depressed ceramic surface or composite resin; and mixed, which included the above two types of failures in the same specimen. Each specimen was evaluated by one calibrated practitioner blinded to treatment group.

4. Statistical analysis
The bond strength values of each group were recorded in a Microsoft® Office Excel database directly from the universal mechanical testing machine. The statistical analysis for SBS was performed with SPSS (Ver. 21.0; SPSS, Chicago, IL, USA).

A two-way analysis of variance (ANOVA) followed by Tukey’s honestly significant difference (HSD) post hoc test (α=0.05) was conducted for the SBS data analysis. Failure mode was performed with descriptive analysis. Unless otherwise indicated, p values less than 0.05 were considered to be statistically significant in all tests.

Part II: Evaluation of clinical performance of the two repair systems in vivo

1. Subject description
A total of 40 patients with 27 women and 13 men possessing 60 porcelain cracked metal-ceramic restorations were involved in the present study. The age of patients were from 18 to 65 years old (mean age of 45 years).

The including standard: the one who had porcelain cracks or chips on metal-ceramic restorations with partial metal exposure (the ratio of exposed metal and porcelain on one surface was not higher than 1:1).

The excluding standard: ceramic cracks caused by wrong design; the cracks happened on occlusal surface or including substantial incisal margin.

The clinical evaluation and treatment was conducted from Oct. 2018 to Jan. 2020. The follow-up examination ended at Apr. 2020. The observation period was ranging from 15 weeks to 82 weeks (mean 65 weeks). This study was approved by the Ethics Committee of Beijing Stomatological Hospital affiliated to Capital Medical University (reference number: CMUSH-IRB-KJ-PJ-2019-01) and carried out in accordance with the Declaration of Helsinki.

2. Clinical research protocol
The patients were randomly and equally divided into two groups: the experimental groups (S), using Singlebond Universal adhesive and Filtek Z350 composite resin to repair restorations with ceramic cracks; the control groups (C), using Ceramic Repair Kit to repair the chipped restorations. All the patients signed an ethical consent. All the repairs were operated by one clinician.

The surface with ceramic cracks were washed for 3 min with 75% ethanol and roughened by a coarse diamond instrument using water irrigation with intermittent strokes for 20 s till the exposed surface shown evident scratches. The margins of the defective ceramic were beveled 2–3 mm with a diamond instrument using water irrigation. Then the surface was rinsed thoroughly with water and dry air with oil-free. If the proximal areas of the restoration were included, a matrix band was placed and secured with a wedge. Cotton rolls were used to isolate the moisture.

In experimental groups (S): the entire surface area which needed to be repaired was applied with Singlebond Universal adhesive by a brush. Excess was remove by compressed air. Then cured by light for 20 s. An opaquer resin (Filtek Z350 XT, 3M ESPE, shade WD) was dispensed to mask the underlying metal. Then light-cure for 20 s. According to the adjacent teeth color, an appropriate Z350 resin was determined and applied in increments of maximum 2 mm and adapted with a suitable instrument to restore the defective protheses. Each layer was light cured individually for 20 s from different directions. Finally excess resin was removed by a suitable fine-grained diamond grinding instrument.

In control groups (C): Monobond N was applied to the exposed ceramic, metal surface using a brush and allowed to react for 60 s. Subsequently, the surface was
dried with oil-free air. Then a thin layer of Heliobond was applied to the entire surface area which needed to be repaired. Excess was removed by compressed air. Then the adhesive was light cured for 20 s. IPS Empress Direct Opaque was used to the prepared metal surface. The layer applied was no more than 0.5 mm thickness. Then it was light cured for 20 s. Tetric N-Ceram was applied in increments of maximum 2 mm and adapted with a suitable instrument to restore the defective restoration. Each layer was light cured individually for 20 s. Finally excess was removed by a suitable fine-grained diamond grinding instrument.

All the repairing resin restorations were performed centric and eccentric occlusal adjustments very carefully and eventually reached light or no occlusal contact to the opposite teeth. Finally, restorations were polished to a high gloss with fine diamond burs and silicone polishers.

The success criteria for the study was as follow: the restoration was in good condition and its color matched with the original one. The failure criteria included chipping of the repaired resin, partial or entire, or its color was significantly different from the original one.

Patients were surveyed every two weeks after repair and enquired the condition of the repaired restoration by telephone or instant messages communications. The patients were required to recall every month. In addition, once they found the repaired restoration was damaged, they were asked to inform the clinician immediately. The duration of the repaired restorations were recorded and then analyzed.

3. Statistical analysis
The survival time of the resin restoration was calculated by means of the Kaplan-Meier (KM) analysis. Statistical differences between the subgroup levels were determined with the Log-rank test (α=0.05). A multivariate Cox regression analysis determined the impact of each covariate, such as repair system, restoration type, location of restoration, jaws and location of cracked ceramic. Other categorical variables were reported as counts and percentages/as means±standard deviation (SD).

RESULTS
Part I: Evaluation of bonding strength of the two repair systems in vitro
The mean shear bond strength and standard deviation of 60 data was shown in Table 2. It was found that the CH group showed the highest bonding strength (15.85 MPa), while the SP group showed the lowest bond strength (13.04 MPa). It was determined through the two-way classification ANOVA that neither the repair system nor the substrate had statistically significant (Table 3) differences in bond strength. The SNK multiple range test demonstrated no significant differences between each substrates (Table 4).

Predominant failure types of the separated interfaces examined by SEM were shown in Table 5 and Fig. 2. For

Table 2 The mean shear bond strength and standard deviation

| Group (n=10) | Repair material         | Substrate       | Mean (SD) (MPa) | Min (MPa) | Max (MPa) | p value* |
|-------------|-------------------------|-----------------|-----------------|-----------|-----------|----------|
| SM          | Singlebond Universal    | Metal           | 13.97 (3.43)    | 10.64     | 19.92     | 0.363    |
| CM          | Ceramic Repair Kit      | Metal           | 15.20 (2.20)    | 11.75     | 18.18     | —        |
| SP          | Singlebond Universal    | Porcelain       | 13.04 (2.18)    | 10.43     | 17.02     | 0.076    |
| CP          | Ceramic Repair Kit      | Porcelain       | 15.45 (2.66)    | 11.20     | 20.34     | —        |
| SH          | Singlebond Universal    | Metal-Porcelain | 15.33 (4.01)    | 9.01      | 21.12     | 0.695    |
| CH          | Ceramic Repair Kit      | Metal-Porcelain | 15.85 (3.00)    | 11.68     | 21.92     | —        |

*p Values less than 0.05 were considered to be statistically significant.

Table 3 Results of two-way classification ANOVA

| Source                  | Type III sum of squares | df | Mean square | F      | p value* |
|-------------------------|-------------------------|----|-------------|--------|----------|
| Repair system           | 35.952                  | 1  | 35.952      | 3.865  | 0.054    |
| Substrate               | 22.463                  | 2  | 11.231      | 1.208  | 0.307    |
| Repair system X substrate| 58.415                 | 3  | 19.472      | 2.093  | 0.111    |
| Total                   | 13,592.074              | 60 | —           | —      | —        |
| Corrected total         | 579.275                 | 59 | —           | —      | —        |

*p Values less than 0.05 were considered to be statistically significant.
Table 4  Results of the SNK test for substrate

| Substrate          | Mean shear strength (MPa) | SNK groups* |
|--------------------|---------------------------|-------------|
| Metal              | 14.34                     | A           |
| Porcelain          | 14.25                     | A           |
| Metal-Porcelain    | 15.59                     | A           |

*Means with the same letter are not significant different.

Table 5  Classification of the failure mode

| Groups | Adhesive failure% | Cohesive failure% | Mixed failure% |
|--------|-------------------|-------------------|---------------|
| SM     | 100               | 0                 | 0             |
| CM     | 90                | 0                 | 10            |
| SP     | 10                | 90                | 0             |
| CP     | 0                 | 90                | 10            |
| SH     | 0                 | 20                | 80            |
| CH     | 0                 | 20                | 80            |

Part II: Evaluation of clinical performance of the two repair systems in vivo

Among the total 60 ceramic cracked restoration, more than 50% were single crowns (n=31; 51.7%), followed by fixed dental prostheses (FDP) (n=16; 26.7%) and splinted crowns (n=13; 21.7%). The restoration involved in maxillary and mandibular owned almost equal proportion, respectively 48.3% and 51.7%. The majority of restoration were located in the molar region (n=31; 51.7%), followed by premolar (n=15; 25%) and then anterior teeth (n=14; 23.3%). Around 55% (n=33) of the restoration, the cracked ceramic region occurred in functional cusps, with the remaining (n=27; 45%) occurring in non-functional cusps (Table 6).

The overall survival rates at 1-, 6-, 12-month were of 70.0%, 56.3%, 54.4% according to the KM curve (Fig. 3). The KM curve of stratified variables were shown respectively (Figs. 4–8). The failures happened mostly within the first 4 weeks after repair (Figs. 3–8).

For the survival analysis, we used the log-rank tests analyzing univariate and found that there was no significant differences between the experimental and control group, meaning that the repair system did not affect the survival time of repaired restoration. Simultaneously, the restoration type and jaws were also non-significant. However, statistically significant differences were found in the comparison where the teeth located and where the ceramic cracked happened (p<0.05). Compared to molars, anterior teeth had a higher survival rate after repair (Fig. 7). Referred to the location of cracked ceramic, repairing the non-functional cusps had a better result than functional cusps (Fig. 8). Data were shown in Table 6.

A Cox regression test were used to conduct the multivariate analysis, whether the repair system, restoration type, jaws, teeth location, crack location were the risk factors associated with the overall survival rate. The results showed none of these variables was significant (Table 7).
Table 6  Univariate statistical analyses

| Variable            | Frequency | Percentage | p value* |
|---------------------|-----------|------------|----------|
| Repair system       |           |            |          |
| S                   | 30        | 50.0       | 0.241    |
| C                   | 30        | 50.0       |          |
| Restoration type    |           |            |          |
| Single crown        | 31        | 51.7       |          |
| Splinted crown      | 13        | 21.7       | 0.619    |
| FDP                 | 16        | 26.7       | 0.314    |
| Jaws                |           |            |          |
| Maxillary           | 29        | 48.3       | 0.139    |
| Mandibular          | 31        | 51.7       |          |
| Teeth location      |           |            |          |
| Anterior teeth      | 14        | 23.3       |          |
| Premolar            | 15        | 25.0       | 0.196    |
| Molar               | 31        | 51.7       | 0.048    |
| Crack location      |           |            |          |
| Functional cusp     | 33        | 55.0       | 0.025    |
| Non-functional cusp | 27        | 45.0       |          |

*p Values less than 0.05 were considered to be statistically significant.

DISCUSSION

Removal and remaking a cracked indirect restoration is acknowledged costly and time-consuming. Repairing restorations intraorally using composite resin is a minimally invasive and more cost-benefit approach than a total replacement, which is also preferred by both clinicians and patients\textsuperscript{11}. For PFM restorations, porcelain cracks are often seen with both porcelain and metal exposed clinically\textsuperscript{20}. Thus, the novel multipurpose universal adhesive systems seem to be an optimal choice for repair since it can be applied on various interface involving tooth, resin, metal and porcelain. Considering results in the present study, the null hypothesis that
Table 7  Multivariate Cox-regression analyses showing risk factors associated with overall survival rate

| Variable          | $p$   | Hazard ratio | 95% Confidence interval |
|-------------------|-------|--------------|-------------------------|
|                   |       |              | Lower | Upper |
| Repair system     | 0.599 | 0.797        | 0.343 | 1.855 |
| Restoration type  | 0.435 | —            | —     | —     |
| Single crown      | Ref   | Ref          | Ref   | Ref   |
| Splinted crown    | 0.823 | 1.139        | 0.363 | 3.576 |
| FDP               | 0.276 | 2.006        | 0.574 | 7.010 |
| Jaws              | 0.902 | 1.073        | 0.347 | 3.317 |
| Teeth location    | 0.652 | —            | —     | —     |
| Anterior teeth    | Ref   | Ref          | Ref   | Ref   |
| Premolar          | 0.367 | 0.498        | 0.110 | 2.260 |
| Molar             | 0.608 | 0.773        | 0.289 | 2.068 |
| Crack location    | 0.185 | 2.212        | 0.684 | 7.150 |
the universal adhesive would not demonstrate lower performance than the conventional ceramic repair system was not rejected. The two repair strategies were considered equivalent. Some researchers came to similar conclusion in vitro. Ito et al. found that it made no difference between universal adhesives and conventional system for the bond strength on feldspathic ceramic reinforced with leucite in lab.

The service life of cracked restorations may be prolonged by repairing while the longevity of the repairing depends on the adhesive capability. So far various surface treatment method have been studied to improve bond strength, which often acts on increasing surface energy and promoting adhesion by mechanical and chemical interactions. For the mechanical methods, diamond bur, airborne particle abrasion and acid etching are commonly used in the purpose to roughen the adhesive surface. However, there is no consensus on the best surface treatment method under different clinical circumstances. The airborne particle abrasion was proven an effective method to increase bond strength, but the surface may be contaminated by the alumina powder particles and they potentially produce micro-crack further damaging or even losing excess lamina of porcelain during the blasting. Wahsh and Ghallab claimed that a diamond bur produced a more irregular and rougher ceramic surface, which had a significantly higher bond strength to resin than airborne abrasion. Other researchers also convinced grinding by a diamond bur created micromechanical retentions and then provides interpenetration of bonding agent to promote adhesive capability. Moreover, using a diamond bur to roughen the cracked surface is the most accessible and easiest way during clinical practice. Silva and Ghadimi et al. reported that surface grinding followed by the application of universal adhesive system was the best option for repairing cracks of the polymer-infiltrated ceramic network and for bonding resin to base-metal alloy. Thus, grinding was applied to roughen the ceramic cracked surface in this study. The application of acid is another mechanical method to enhance bond strength. It is known that hydrofluoric acid (HF) was recommended for silica-based ceramics, which can roughen the adhesive surface and increase mechanical interlock with composite resin. However, referring to the intense corrosive characteristics of HF when used intraorally, it was eliminated in our in vivo study for the sake of reducing hazards. In addition, HF was inefficient for metal substrate since it was unable to break metallic bonds. Considering the consistency of the study, HF was omitted in our in vitro study as well. Similarly, the application of phosphoric acid cannot increase the micromechanical interlock effect to the ceramic or metal surface but only has the cleaning effect after mechanical roughening. Thus, the phosphoric acid was not applied in the present study too.

For the chemical methods, silane coupling agents are often involved, which both of our tested materials contain. Silane coupling agent is a kind of adhesion promoter, which enhances both organic and inorganic surface to produce chemical bonds. 3-methacryloyloxypropyltrimethoxysilane (MPS), the silane coupling agent, is the key reactive component of Monobond N. MPS is a bifunctional molecule: one methacrylate group reacts with resin matrix; the other silanol group reacts with ceramic/metal substrate surface creating a siloxane bond (Si-O-Si). Besides silane, MDP is another important constituent coexisted in Singlebond universal adhesive. MDP is a phosphoric acid ester monomer, which has been widely added into primer, adhesive and resin cement to promote bond strength. MDP has bifunctional groups, a hydrophilic phosphoric acid group and a hydrophobic carboxylic acid group, which are connected by a long organic carbochain. The hydrophilic phosphate ester group bonds to the metal surface and carboxylic acid group reacts with the monomers of the resin composite. A research found that MDP containing resin cements appear to be the most effective one.

The first part of the present study tested the shear bond strength of composite resin to different substrate surfaces in vitro. It imitated cracked porcelain in PFM restorations under different situations: cracks within porcelain, cracks with entire metal exposure, and cracks with porcelain and partial metal exposure. According to the previous studies, repairs of cracked restorations of noble or non-noble alloy substrates were not as effective as ceramic substrates. However, our results turned out that all the specimen showed a similar bonding strength value with no statistically significant differences regardless of the substrate surface and adhesive system. On one hand, this may be on account of the improvement and development of the active ingredient of the primers and adhesives, which further promoted the bond strength to the metal surface. On the other hand, HF was not applied in the present study, which may decrease the bond strength of ceramic groups. Moreover, our study indicated that the porcelain surface with Singlebond Universal adhesive showed a relatively lower bonding strength compared with the porcelain surface group processed with Ceramic Repair Kit, though there was no significant difference. A meta-analysis also revealed the bond strength to feldspathic porcelain did not differ statistically when universal adhesive or silane-based primer were used. Although the universal adhesives containing two active ingredients, the MDP and silane agent, some researchers found that the low pH value caused by the acidic MDP monomer may dehydrate silane’s self-condensation and make it unstable further weaken its effectiveness. Consequently, the bond strength for the porcelain group with Singlebond Universal adhesive seemed unsatisfied. Even though, the universal adhesives had a fine performance in metal and metal-ceramic groups, indicating the MDP may play an important role in metal surface. The mechanism was that MDP monomers contained in primers or adhesives had better bond strength to chromium oxide, which was easily created on the casting Co-Cr metal surface, producing strong adhesion. Its phosphoric acid group end bonded to chromium oxide; while, the other end was copolymerized with resin monomers.
Thus, an additional adhesive force between such MDP monomers and the oxide layer exposed on the metal alloy surface can be expected.

Some research demonstrated that the silane may occur pre-hydrolyzed and lost its initial activity after a long time storage\(^{53,54}\). Yao et al.\(^{57}\) reported that the bonding strength to glass-ceramic of silane stored for 2 h was significantly higher than the silane stored for 10 days. While the silane in Ceramic Repair Kit has 24 months for its quality guarantee period according to the manufacturer’ indication, the effectiveness may decrease in the later period of its service life. However, the multipurpose universal adhesive, which can be applied under various circumstances, will accelerate the renewing cycle and keep high activity during its service life. Since the Ceramic Repair Kit and Singlebond Universal adhesive had similar bonding efficiency based on the experimental conditions and methodology used in this study, the easier and timesaving method with one bottle universal adhesive was recommended.

The failure mode of the present study suggested that repair system performed differently depending on substrate. The largest number of cohesive failures in the present study was found in SP and CP group (both were 90%), whose substrate both were porcelain. The effective chemical mechanism may explain the cohesive failure mode occurred in porcelain other than in adhesive interface. The repair system brought about so strong bond strength that united the resin and ceramic to be an entirety. When they were fatigue, the separation may arise within the material. Therefore, the bond strength of porcelain group may be related to the mechanical strength of the substrate and resin. Since the metal was not easy to damage, the failure mode of the metal groups were mainly adhesive. For the metal-ceramic groups, it also followed the above rules, which showed mixed failure mostly. Some researchers thought it was due to the non-uniform stresses within the interfacial zone generated by shear testing that had a significant effect on the mode of failure\(^{59}\). Yet given that restorations especially anterior ones with axial ceramic chipped were subjected mainly to shear stresses, testing shear strength was suitable for assessing the composite repair ability.

Due to the complexity of the intraoral environment, it was hardly to predict the intensity and mode of stresses exerted on a restoration clinically. The result in laboratory cannot represent the situation of oral environment. Thus, the second part of the present study was intraorally repairing ceramic cracked restoration with different repair systems. There is little or no literatures about the clinical repair performance.

In the present study, failures showed no relation to the repair system, type of restoration and jaws. Only the teeth and cracked ceramic location made difference on the restoration’s survival time. The repairing resin on non-functional cusps had an obviously higher survival rate than that on functional cusps. We speculated that there may be an excessive occlusal shear strength on functional cusps. This intermittent load may lead to dimensional deformation in loading-bearing areas\(^{60}\), which was inclined to debonding the resin from the cracked surface further caused repairing failure. This shear strength may also be the reason of the first ceramic crack. Therefore, the occlusal adjustment should be made precisely whatever the initial or repaired restoration. Likewise, the anterior teeth afforded less occlusal force compared to molars, so they possessed higher successful rate after repairing if paid attention to.

In the present study, the overall survival rates at 1-, 6-, 12-month were 70.0%, 56.3%, and 54.4% respectively. Some researchers found that the effectiveness of cohesive strength of silane infiltrated into the micro-retentions would gradually decrease after some time in water\(^{50}\). This may partially explain the survival rate decreased over time. Substantial failures occurred within the first 4 weeks, which was in coincidence with other literatures\(^{61}\). For the long term success, the splinted crowns had the lowest survival rate viewed from the KM curves. The inappropriate design may be the reason of the high failure rate. The different mobility of each teeth under functional status caused an excessive shear strength focused on the joint of the splinted crowns, which may not only led to the first ceramic crack but also the second repairing resin failure.

Although there is still no consensus on the minimal bond strength for successful bonding, a reasonable goal of 20 MPa (composite to dentin) has been acceptable\(^{62}\). Considering the results in the \textit{in vitro} part of our study, the bond strength ranged from 13 MPa to 16 MPa with the two different repair system using our methodology, which was reasonable according to others’ reports (ranging from 1.09–29.9 MPa)\(^{57}\). The actually intraoral bond strength was supposed to be lower than the data got from laboratory. Consequently, regarding of the adhesive strength and clinical performance, the repairing method for cracked ceramic restoration, especially for functional region of molars, is still limited only for provisional or emergent usage. However, in some indications, such as labial surface of anterior teeth, repairing a ceramic cracked restoration may be a good alternative.

The observation period in our study was ranging from 15 weeks to 82 weeks. Longer observation time may be expected in the future. Furthermore, we have confirmed the universal adhesive had similar performance to commercial ceramic repair kit for PFM cracks repairing in the present study, additional clinical studies are required to support the feasibility and protocols of such adhesive to repair lithium disilicate glass ceramic and zirconia protheses.

**CONCLUSIONS**

1. The universal adhesive and traditional resin composite had a similar bond strength on different substrate compared to commercial ceramic repair kit.
2. The bond strength of the two different repair system had a similar repair performance in repairing the porcelain cracked restorations and they both met the clinical need under appropriate
indications.

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CONFLICTS OF INTEREST
Declarations of interest: none.

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