



Research Article

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A novel porous silica-zirconia coating for improving bond performance of dental zirconia

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Abstract: Objective: To coat a zirconia surface with silica-zirconia using a dip-coating technique and evaluate its effect on resin-zirconia shear bond strength (SBS). Methods: A silica-zirconia suspension was prepared and used to coat a zirconia surface using a dip-coating technique. One hundred and eighty-nine zirconia disks were divided into three groups according to their different surface treatments (polishing, sandblasting, and silica-zirconia coating). Scanning electron microscopy (SEM), energy dispersive X-ray (EDX), and X-ray diffraction (XRD) were used to analyze the differently treated zirconia surfaces. Different primer treatments (Monobond N, Z-PRIME Plus, and no primer) were also applied to the zirconia surfaces. Subsequently, 180 composite resin cylinders (Filtek Z350) were cemented onto the zirconia disks with resin cement (RelyX Ultimate). The SBS was measured after water storage for 24 h or 6 months. The data were analyzed by two-way analysis of variance (ANOVA). Results: SEM and EDX showed that the silica-zirconia coating produced a porous layer with additional Si, and XRD showed that only tetragonal zirconia was on the silica-zirconia-coating surface. Compared with the control group, the resin-zirconia SBSs of the sandblasting group and silica-zirconia-coating group were significantly increased ($P < 0.05$). The silica-zirconia coating followed by the application of Monobond N produced the highest SBS ($P < 0.05$). Water aging significantly reduced the resin-zirconia SBS ($P < 0.05$). Conclusions: Dip-coating with silica-zirconia might be a feasible way to improve resin-zirconia bonding.

Key words: Silica-zirconia coating; Zirconia; Bond performance; Shear bond strength (SBS)

1 Introduction

Zirconia is widely used in dentistry due to its excellent mechanical properties, biocompatibility, and favorable esthetic characteristics (Tabatabaian, 2019). However, the strength and durability of the resin-zirconia bond remain a challenge. A reliable standardized adhesive protocol has not been achieved (Blatz et al., 2018) and this has restricted the application of zirconia in adhesive dentistry. Recently, to improve the bond performance of zirconia, different treatments of the zirconia surface have been investigated (Thammajaruk et al., 2018), including chemical and physical methods, as well as coating techniques.

One of the most common protocols to improve the resin-zirconia bond strength is sandblasting with alumina particles, followed by application of an adhesive primer containing 10-methacryloyloxydecyl dihydrogenphosphate (10-MDP) (Kern, 2015). Sandblasting zirconia with 110- μm alumina particles for 20 s resulted in high surface roughness and thus improved the resin-zirconia shear bond strength (SBS) (Zhao et al., 2020). 10-MDP could also enhance resin-zirconia bonding (Go et al., 2019) because it might have chemical linkages with zirconia via P-O-Zr bonds (Lima et al., 2019). However, sandblasting may produce surface flaws in the zirconia and trigger transformation from a tetragonal to a monoclinic crystal phase (Fonseca et al., 2013), which affects the mechanical properties of zirconia. Moreover, previous studies also reported that the bond strength of resin-zirconia following 10-MDP treatment was not as strong or durable as that of resin-silica ceramic following hydrofluoric acid etching and

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silanization treatments (Attia, 2011; Keshvad and Hakimaneh, 2018).

Coating techniques are important for improving bond performance without causing surface damage to the zirconia (Karthigeyan et al., 2019). A silica coating on a zirconia surface combined with a silane-coupling agent has been a promising method to improve resin-zirconia bonding (Nagaoka et al., 2019). In the tribochemical silica-coating technique, a zirconia surface is bombarded with silica-coated aluminum oxide particles to create a silica coating and increase the surface roughness (Lim et al., 2018). This is the simplest method to produce a silica layer, but the tribochemical silica coating is not firmly attached to the zirconia substrate (Nishigawa et al., 2008). Similarly, the sol-gel technique could also be used to produce a silica coating, by forming silanols via the hydrolysis of tetraethyl orthosilicate, resulting in the deposition of silica particles with the condensed silanols on the zirconia surface (Madani et al., 2016). However, the sol-gel silica coating is smooth and prone to crack after thermal treatment (Chen et al., 2013). Other methods used to form silica coatings on zirconia surfaces include reactive magnetron sputting and silicon nitride hydrolysis, but these are considered too complicated and expensive (Queiroz et al., 2012; Lung et al., 2015).

A zirconia coating on a zirconia substrate is also used to improve resin-zirconia bonding (Aboushelib, 2012). Fusion sputtering technique has been used to produce a porous zirconia layer by spraying an air-water jet carrying zirconia particles onto unsintered zirconia frameworks. Subsequently, the zirconia particles are fused with the underlying framework after sintering (Aboushelib, 2012). This can create undercuts and rough surfaces to facilitate micromechanical interlocking with resin cement. Phark et al. (2009a, 2009b) coated zirconia with slurry containing zirconia powders and pore formers. The slurry-coated zirconia was then sintered, and with the pore formers burned out, a porous zirconia surface was formed. Zirconia coatings, predominantly depending on mechanical interlocking (Aboushelib et al., 2018), could yield a firm attachment to a zirconia substrate after sintering because they are of the same material (Ali et al., 2019).

Chen et al. (2012) reported coating a thin layer of flowable composite resin containing silica and zirconia nanofillers on a zirconia surface with a micro-brush, which was sintered at 1200 °C to form a silica-zirconia

coating. A silica-zirconia coating in combination with silane could greatly improve resin-zirconia bond strength, but it is difficult to control the thickness and homogeneity of the coating (Chen et al., 2012).

In this study, we created a porous silica-zirconia coating on a zirconia substrate using a dip-coating technique, to improve the bond performance of zirconia. The aims of this study were (1) to produce a porous silica-zirconia coating on a zirconia surface, and (2) to evaluate the effect of the silica-zirconia coating on resin-zirconia SBS. The null hypotheses tested were that the dip-coating technique could not produce a porous silica-zirconia coating on zirconia substrate, and that the silica-zirconia coating would not improve the resin-zirconia bond strength.

2 Materials and methods

The materials used in this study are listed in Table 1.

2.1 Preparation of silica-zirconia suspension

Silica and zirconia nanopowders were respectively ground in an agate mortar for 20 min before use. A total of 35 mg of polyethylene glycol 2000 and 20 mL of ethanol-aqueous (1:1, volume ratio) solution were mixed until completely dissolved. To this solution, 0.20 g of silica nanopowder was added and stirred magnetically for 20 min to form a suspension. Next, 0.50 g of zirconia nanopowder was added to the suspension and stirred as before. The suspension was then ultrasonically dispersed for 60 min. Particle-size analysis was performed with a Zetasizer Nano size analyzer (Malvern Instruments Ltd., UK) and a drop of suspension was dripped on a silicon chip and observed using a scanning electron microscope (Hitachi su8010, Tokyo, Japan).

2.2 Preparation of zirconia disks

Unsintered zirconia was cut into disks with 12.4 mm diameter and 2 mm height using a computer-assisted design/computer-assisted manufacturing (CAD/CAM) system (Amann Girrbach, Koblach, Austria) and a low-speed saw (Buehler Isomet, Lake Bluff, USA). The zirconia disks were then polished with 1000-grit SiC paper under water cooling for 20 s, ultrasonically cleansed in deionized water for 10 min, and then

dried at 60 °C in an oven (STIK BAO-150A, Shanghai, China) for 10 min.

One hundred and eighty-nine zirconia disks were randomly divided into three groups according to the different surface treatments as follows: (1) Group A (control group): the disk surfaces had no further treatment before or after sintering; (2) Group B: after sintering, the disk surfaces were sandblasted (Refert Vario Basic, Germany) with 110- μm aluminum oxide at a pressure of 0.3 MPa at a distance of 10 mm for 20 s (Zhao et al., 2020); (3) Group C: the disks were dipped into the aforementioned suspension at a speed of 3 mm/min with a universal testing machine (Instron5960, Norwood, USA) until totally submersed, and kept still for 60 s. They were then lifted out of the suspension at the same speed. Then the disks were dried in air at room temperature for 2 h before being sintered in an oven (Wieland Dental, Pforzheim, Germany) according to the manufacturer's instructions. The sintering parameters are listed in Table 2.

Two disks randomly selected from each group were analyzed with scanning electron microscopy (SEM), an energy dispersive X-ray detector (EDX; Escalab, UK), and X-ray diffraction (XRD; PANalytical B.V X-pert Power, Holland). One disk was split and the fractured surface was observed using SEM.

2.3 Shear bond strength testing

Each group was further divided randomly into three subgroups ($n=20$) according to the different surface treatments. Monobond N and Z-PRIME Plus primers were applied to the disk surfaces (except in the case of the control) strictly according to the manufacturers' instructions.

To produce composite resin cylinders, 180 transparent plastic tubes with an inner diameter of 3 mm and a height of 3 mm were filled with composite resin and then light-cured with an intensity output of 1200 mW/cm² (3M ESPE Elipar S10, St. Paul, USA) for 40 s.

Table 1 Materials used in this study

Material	Manufacturer	Lot No.	Composition
Silica nanopowder	Aladdin Industrial Corporation, Shanghai, China	B1513025	SiO ₂
Zirconia nanopowder	Wanjing New Material Corporation, Hangzhou, China	20170703	ZrO ₂
Dispersant	Sinopharm Chemical Reagent Corporation, Shanghai, China	20170207	Polyethylene glycol 2000
Zirconia disks	Wieland Dental, Germany	U29273	ZrO ₂ , HfO ₂ , Y ₂ O ₃
Aluminum oxide	Renfert GmbH, Hilzingen, Germany	15831005	Al ₂ O ₃
Monobond N	Ivoclar Vivadent AG, Liechtenstein	W85815	Alcohol solution of silane methacrylate, phosphoric acid methacrylate, sulphide methacrylate
Z-PRIME Plus	Bisco, Schaumburg, IL, USA	1800000975	Biphenyl dimethacrylate, HEMA, MDP, ethanol
Composite resin	3M ESPE Filtek Z350, USA	N820167	Bis-GMA, UDMA, TEGDMA, PEGDMA, Bis-EMA, silica/zirconia cluster filler
RelyX Ultimate clicker cement	3M ESPE, USA	3745504	Base paste: methacrylate monomers, radiopaque, silanated fillers, initiator components; Catalyst paste: methacrylate monomers, radiopaque alkaline fillers, initiator components

HEMA: 2-hydroxyethyl methacrylate; MDP: methacryloxydecyl dihydrogen phosphate; Bis-GMA: bisphenol A diglycidylmethacrylate; UDMA: urethane dimethacrylate; TEGDMA: triethylene glycol dimethacrylate; PEGDMA: polyethylene ethylene glycol dimethacrylate; Bis-EMA: bisphenol A ethoxylated dimethacrylate.

Table 2 Sintering procedures and parameters of zirconia disks

No.	Procedure	Temperature 1 (°C)	Temperature 2 (°C)	Ramp up rate (°C/h)	Holding time (h)
1	Ramp up phase	20	900	600	
2	Holding phase	900	900	0	0.5
3	Ramp up phase	900	1450	200	
4	Holding phase	1450	1450	0	2.0
5	Cooling phase	1450	900	600	
6	Cooling phase	900	20	500	

The composite resin cylinders were cemented onto the treated disks with RelyX Ultimate clicker cement, and the cement units were pressed at 500 g poise for 3 min. Excess cement was wiped off and the specimens were light cured for 20 s each quadrant.

SBS was measured with a universal testing machine (Instron5960, Norwood, USA) at a crosshead speed of 0.5 mm/min after the specimens were stored in distilled water at room temperature for 24 h or 6 months (with the distilled water changed every week). The bond strength was measured in megapascals (MPa).

2.4 Analysis of failure modes

The fractured zirconia surfaces after SBS testing were examined with a stereo microscope (Olympus SZ61, Tokyo, Japan) and failure modes were classified into three types as follows: Type 1 (adhesive failure), no cement was visible on the fractured zirconia surface; Type 2 (mixed failure), partial cement and partial zirconia surfaces were visible on the fractured surface; Type 3 (cohesive failure), almost all the fractured zirconia surfaces were covered with cement.

2.5 Statistical analysis

Statistical analysis was performed using SPSS 24.0 software (IBM SPSS, Chicago, IL, USA). The Kolmogorov-Smirnov test and Levene's test were used to check normality and equal variance, and then the SBS values were analyzed by two-way analysis of variance (ANOVA) followed by a post-hoc least significant difference (LSD) test for multiple comparisons (Lung et al., 2015). The significance level was set at $\alpha=0.05$.

3 Results

3.1 Characterization of suspension

The silica-zirconia suspension was a milky white homogeneous liquid and no precipitation took place after the suspension was kept still for 2 h.

Particle-size analysis showed that the particle sizes of the suspension were in the range of 10–1000 nm with a single peak at 213.3 nm (Fig. 1a). SEM images showed that the size of the particles was 50–500 nm (Fig. 1b).

3.2 Surface characterization of treated zirconia disks

The SEM images showed that the polished zirconia surfaces were smooth, with some polished scratches

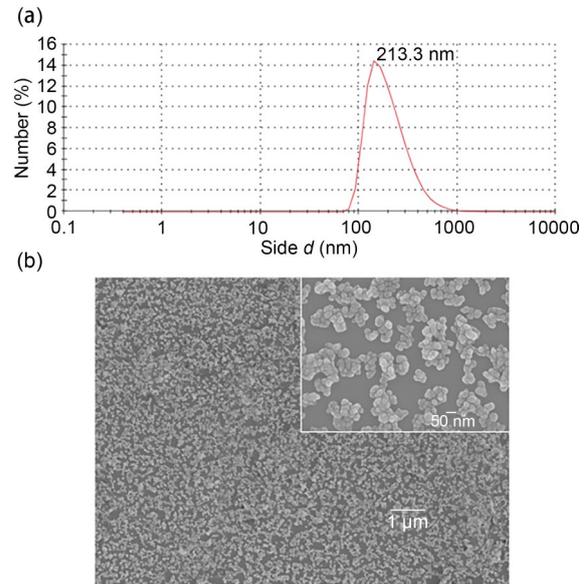


Fig. 1 Size distributions of nanoparticles in the suspension. (a) The percentage of particles of different sizes in suspension in the range of 10–1000 nm, with a single peak at 213.3 nm; (b) Scanning electron microscopy (SEM) images of particles of 50–500 nm.

remaining, and zirconia crystal grains were in close contact without any gaps at high magnification. SEM images of the fractured surface revealed no silica-zirconia coating on the polished zirconia surface (Fig. 2a). The sandblasted zirconia had a rough and irregular surface without any characteristics of zirconia crystal grains at high magnification. The SEM images of the fractured section also showed no silica-zirconia coating on the sandblasted zirconia surface (Fig. 2b). At high magnification, the surfaces coated with silica-zirconia had homogeneously distributed nanoparticles with numerous micro-gaps among crystal grains. A coating layer of about 3–5 μm thickness was detectable on the fractured section of the silica-zirconia-coated zirconia (Fig. 2c).

The EDX spectrum revealed the presence of the elements Zr, O, Y, C, and Hf on the zirconia surface in the control group (Fig. 3a), Zr, O, Y, C, Hf, and Al on the sandblasted surface (Fig. 3b), and Si, Zr, O, C, Al, Na, and Os on the silica-zirconia-coated surface (Fig. 3c). The elements map on the silica-zirconia-coated surface showed that the distributions of Si and Zr elements were homogeneous (Fig. 3c).

Fig. 4 shows the XRD spectra of the different surfaces. For the control group and silica-zirconia-coated group, there were peaks at 30.3° , 35.2° , 50.5° , 60.0° , and 62.8° , representing crystal planes (101),

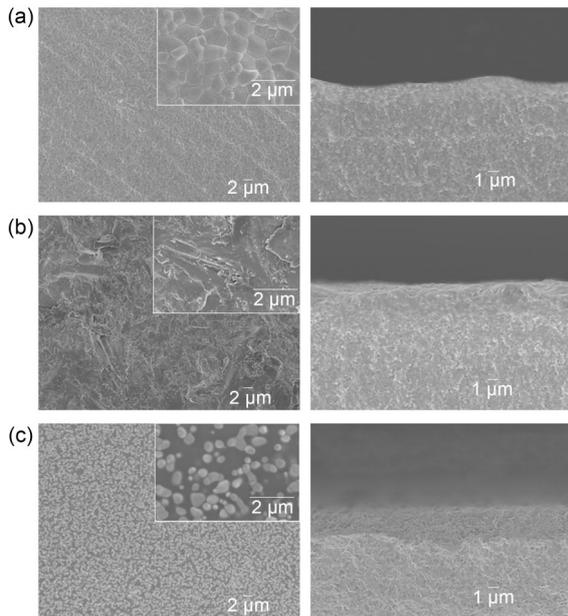


Fig. 2 Scanning electron microscopy (SEM) images of the treated zirconia surfaces. (a) Control group: surfaces are smooth and zirconia crystal grains are in close contact with no gaps at high magnification, and there is no coating on the fractured surface. (b) Sandblasted group: rough and irregular surface without any characteristics of zirconia crystal grains at high magnification, and no coating on the fractured surface. (c) Silica-zirconia-coated group: homogeneously distributed nanoparticles with numerous micro-gaps among crystal grains at high magnification, and a coating of about 3–5 μm thickness on the fractured surface.

(110), (112), (211), and (202), respectively, which are characteristics of tetragonal zirconia (Chintapalli et al., 2013). For the sandblasted group, there was another peak at 28.2°, demonstrating that 12.2% of the sandblasted surface was coated with monoclinic zirconia (Chintapalli et al., 2013).

3.3 Shear bond strength data

Table 3 shows the mean SBS values and their standard deviations for the different treatments and different water storage periods. Two-way ANOVA showed that the surface treatments and the storage periods significantly affected the SBS ($P<0.05$). Silica-zirconia-coated zirconia surfaces treated with Monobond N produced the highest SBS in all the groups ($P<0.05$). The sandblasted zirconia surface treated with Z-PRIME Plus showed significantly higher SBS than that of the control group ($P<0.05$). Table 4 shows the distribution of the percentage and number of failure modes in each group.

4 Discussion

4.1 Shear bond strength

In the present study, both surface treatments and water aging significantly influenced the zirconia SBS ($P<0.05$). The polished zirconia surface of the control

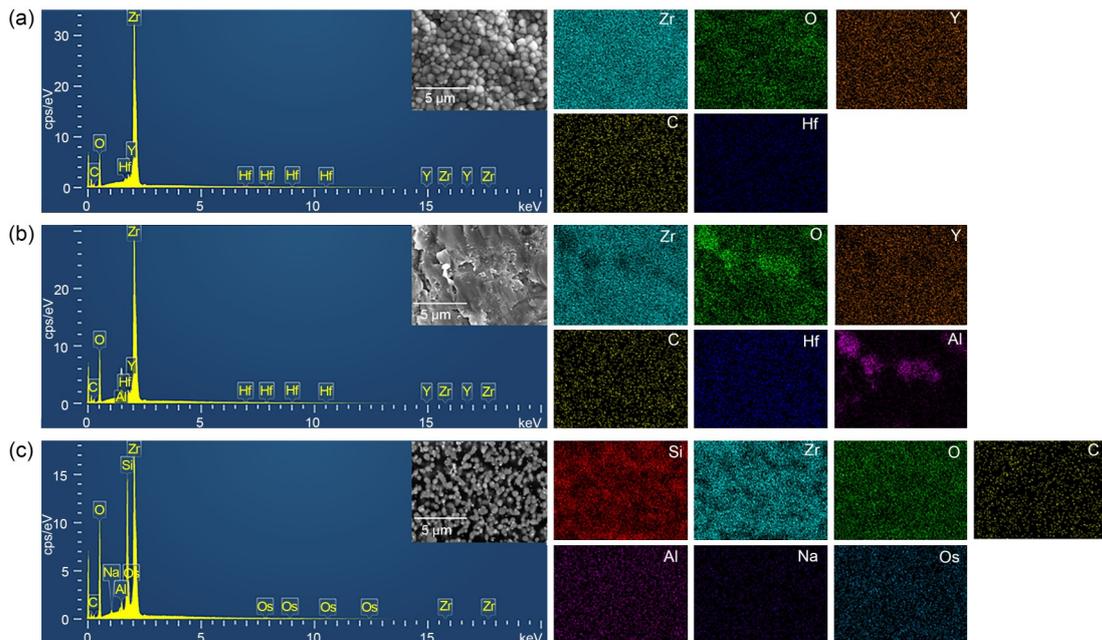


Fig. 3 Energy dispersive spectrometer (EDS) spectra of the treated zirconia surfaces and maps of the elements. (a) Control group; (b) Sandblasted group; (c) Silica-zirconia-coated group. cps: counts per second.

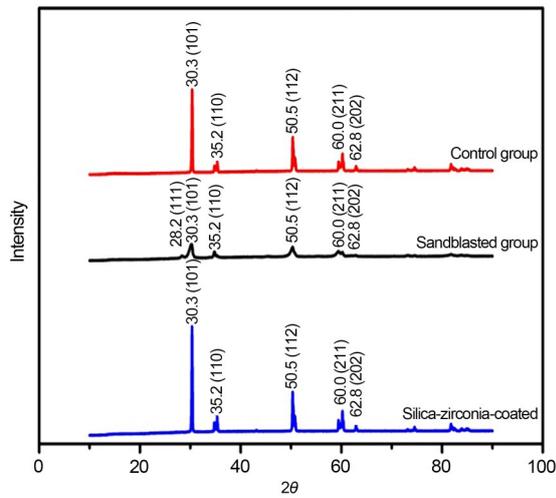


Fig. 4 X-ray diffraction (XRD) spectra of different treated surfaces. Peaks at 30.3°, 35.2°, 50.5°, 60.0°, and 62.8° in all three groups, representing crystal planes (101), (110), (112), (211), and (202), respectively, of tetragonal zirconia. Another peak at 28.2° on the sandblasted surface represents crystal plane (111) of monoclinic zirconia.

group produced the lowest SBS and the failure mode was mainly adhesive failure (Table 4). This is in line with previous studies (Park et al., 2018; Ruales-Carrera et al., 2019). Compared with the control, sandblasted zirconia surfaces significantly increased the zirconia SBS ($P<0.05$; Table 3), regardless of the application of primers. Sandblasting followed by the application of Z-PRIME Plus yielded the highest SBS among the sandblasted groups ($P<0.05$). Sandblasting followed by application of MDP-containing primers is a recommended method for zirconia bonding (Özcan and Bernasconi, 2015; Saleh et al., 2019), because sandblasting can increase the surface energy and roughen the surface (Kim et al., 2011), and MDP can significantly increase

the zirconia SBS via chemical bonding (Xie et al., 2015). In the present study, the silica-zirconia-coated surfaces treated with Monobond N produced the highest SBS among all the groups ($P<0.05$), regardless of the water aging. This demonstrates that silica-zirconia coating is an effective method to improve resin-zirconia bond strength. This might be attributable to micro-interlocking and silanization at the resin-zirconia interface (Wille et al., 2017). SEM images (Fig. 2c) revealed that there were numerous micro-gaps among the particles on the silica-zirconia coating layer. This supports the suggestion that micro-interlocking between zirconia and resin and additional Si element on the zirconia surface provides a silanizable surface for improving bond strength. Therefore, the silica-zirconia coating in this study not only promotes micro-interlocking, but also chemical bonding.

4.2 Silica-zirconia coating

Tribochemical silica coating is one of the most commonly used methods for surface treatment of zirconia (Nagaoka et al., 2019). However, particle abrasion during the tribochemical coating process might lead to surface damage and reduce the fatigue resistance and survival rate of zirconia (Mahmoodi et al., 2016). Moreover, the silica coating created by this method is not firmly attached to the zirconia substrate, and silica particles can be lost from the surface by ultrasonic cleansing (Nishigawa et al., 2008). In the present study, the XRD spectrum showed that there was only tetragonal zirconia on the silica-zirconia-coated zirconia surface, indicating that silica-zirconia coating by dip-coating might not have damaged the zirconia substrate (Chintapalli et al., 2013). However, the sandblasting produced about 12.2% of monoclinic zirconia on the sandblasted surface. This

Table 3 Shear bond strength values of each group

Group	Primer	SBS (MPa)	
		24 h	6 months
Control	No primer	5.23±1.39 ^{Aa}	2.57±1.72 ^{Ba}
	Monobond N	4.35±1.44 ^{Aa}	2.38±1.67 ^{Ba}
	Z-PRIME Plus	9.03±1.64 ^{Ab}	3.62±1.74 ^{Bb}
Sandblasted	No primer	13.38±2.38 ^{Ac}	8.12±1.97 ^{Bc}
	Monobond N	12.27±2.11 ^{Ac}	8.65±2.23 ^{Bc}
	Z-PRIME Plus	18.27±3.13 ^{Ac}	10.65±2.01 ^{Bc}
Silica-zirconia-coated	No primer	10.59±1.91 ^{Ac}	7.91±1.98 ^{Bc}
	Monobond N	21.28±3.03 ^{Af}	16.23±2.17 ^{Bf}
	Z-PRIME Plus	14.39±2.23 ^{Ad}	9.56±1.88 ^{Bd}

The data are described as mean±standard deviation ($n=10$). Shear bond strength (SBS) values were analyzed by two-way analysis of variance (ANOVA) followed by a post-hoc least significant difference (LSD) test for multiple comparisons. Different uppercase letters in the same row mean significant difference ($P<0.05$) between different time points. Different lowercase letters in the same column mean significant difference ($P<0.05$) between different groups.

Table 4 Percentage distribution and numbers of different failure modes

Group	Primers	Storage time	Adhesive failure	Mixed failure	Cohesive failure
Control	No primer	24 h	10 (100%)	0	0
		6 months	10 (100%)	0	0
	Monobond N	24 h	10 (100%)	0	0
		6 months	10 (100%)	0	0
	Z-PRIME Plus	24 h	7 (70%)	3 (30%)	0
		6 months	10 (100%)	0	0
Sandblasted	No primer	24 h	2 (20%)	5 (50%)	3 (30%)
		6 months	7 (70%)	3 (30%)	0
	Monobond N	24 h	3 (30%)	4 (40%)	3 (30%)
		6 months	6 (60%)	4 (40%)	0
	Z-PRIME Plus	24 h	0	3 (30%)	7 (70%)
		6 months	4 (40%)	5 (50%)	1 (10%)
Silica-zirconia-coated	No primer	24 h	5 (50%)	4 (40%)	1 (10%)
		6 months	8 (80%)	2 (20%)	0
	Monobond N	24 h	0	1 (10%)	9 (90%)
		6 months	0	4 (40%)	6 (60%)
	Z-PRIME Plus	24 h	1 (10%)	5 (50%)	4 (40%)
		6 months	6 (60%)	3 (30%)	1 (10%)

The data are described as number (percentage) of different failure modes.

might explain the zirconia surface damage resulting from sandblasting (Chintapalli et al., 2013). Furthermore, silica-zirconia coating followed by application of Monobond N produced the highest SBS, and the predominant failure type was cohesive failure in resin cement. This indicates that the silica-zirconia coating might have been firmly attached to the zirconia substrate. This is in agreement with the findings of Salem et al. (2016) who demonstrated that the zirconia particles could be fused onto the zirconia substrate. Since the high temperature induces a phase change from monoclinic zirconia to tetragonal zirconia during the sintering process it has been stated that the zirconia particles and the zirconia substrate can be sintered together (Chen et al., 2012).

The thickness of the silica-zirconia coating layer in the present study was about 3–5 μm . Therefore, the thickness will not have any influence on the marginal adaptation or the seating of restorations since the American Dental Association (ADA) recommendation of the space between a restoration and dentin is 45 μm (Nassar and González-Cabezas, 2011). Beuer et al. (2009) reported that internal adaptation of less than 120 μm between the dentin and restoration is clinically acceptable. Furthermore, the thickness of the coating could be controlled by changing the concentration of the suspensions, the drying time, or the velocity of dipping and lifting.

4.3 Dip-coating technique

Dip-coating is a simple, appropriate method to form a homogeneous coating on objects with different

shapes (Gans et al., 2019). In the present study, the dip-coating technique was used to create a porous silica-zirconia coating on a zirconia substrate for improving the bond performance of zirconia.

Creating a stable nanoparticle suspension of a mixture of silica and zirconia was the key step enabling dip-coating to form a silica-zirconia coating in the present study. Suitable dispersion methods are very important during the formation of nanoparticle suspensions (Xu et al., 2018), since nanoparticles are apt to agglomerate (Mo et al., 2019). In the present study, grinding, dispersant, and sonication were used to produce a stable silica-zirconia suspension. Grinding silica and zirconia nanopowders in an agate mortar can disperse agglomerated nanoparticles before the suspension is prepared. Polyethylene glycol used as a solvent is an efficient dispersant to reduce the agglomeration of nanoparticles (Feng et al., 2017), and sonication of the suspension is an effective method for dispersing nanoparticles (Baig et al., 2018). No precipitation took place in the present study, even when the suspension was kept still for more than 2 h. In addition, the silica and zirconia particles were well dispersed in the suspension (Fig. 1).

5 Conclusions

According to the limited data in this study, dip-coating with silica-zirconia is a feasible method that could significantly improve resin-zirconia bond strength.

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Author contributions

Zhiwei SU and Baiping FU designed the study. Zhiwei SU performed the experiments. Zhiwei SU and Mingxing LI wrote and edited the manuscript. Ling ZHANG and Chaoyang WANG performed data analysis. Leiqing ZHANG, Jingqiu XU, and Baiping FU contributed to editing of the manuscript. All authors have read and approved the final manuscript and, therefore, have full access to all the data in the study and take responsibility for the integrity and security of the data.

Compliance with ethics guidelines

Zhiwei SU, Mingxing LI, Ling ZHANG, Chaoyang WANG, Leiqing ZHANG, Jingqiu XU, and Baiping FU declare that they have no conflict of interest.

This article does not contain any studies with human or animal subjects performed by any of the authors.

References

- Aboushelib MN, 2012. Fusion sputtering for bonding to zirconia-based materials. *J Adhes Dent*, 14(4):323-328. <https://doi.org/10.3290/j.jad.a25684>
- Aboushelib MN, Ragab H, Arnaot M, 2018. Ultrastructural analysis and long-term evaluation of composite-zirconia bond strength. *J Adhes Dent*, 20(1):33-39. <https://doi.org/10.3290/j.jad.a39962>
- Ali N, Safwat A, Aboushelib M, 2019. The effect of fusion sputtering surface treatment on microshear bond strength of zirconia and MDP-containing resin cement. *Dent Mater*, 35(6):e107-e112. <https://doi.org/10.1016/j.dental.2019.02.013>
- Attia A, 2011. Bond strength of three luting agents to zirconia ceramic—influence of surface treatment and thermocycling. *J Appl Oral Sci*, 19(4):388-395. <https://doi.org/10.1590/s1678-77572011005000015>
- Baig Z, Mamat O, Mustapha M, et al., 2018. Investigation of tip sonication effects on structural quality of graphene nanoplatelets (GNPs) for superior solvent dispersion. *Ultrason Sonochem*, 45:133-149. <https://doi.org/10.1016/j.ultsonch.2018.03.007>
- Beuer F, Aggstaller H, Edelhoff D, et al., 2009. Marginal and internal fits of fixed dental prostheses zirconia retainers. *Dent Mater*, 25(1):94-102. <https://doi.org/10.1016/j.dental.2008.04.018>
- Blatz MB, Vonderheide M, Conejo J, 2018. The effect of resin bonding on long-term success of high-strength ceramics. *J Dent Res*, 97(2):132-139. <https://doi.org/10.1177/0022034517729134>
- Chen C, Chen G, Xie HF, et al., 2013. Nanosilica coating for bonding improvements to zirconia. *Int J Nanomedicine*, 8(1):4053-4062. <https://doi.org/10.2147/IJN.S52145>
- Chen CF, Kleverlaan CJ, Feilzer AJ, 2012. Effect of an experimental zirconia-silica coating technique on micro tensile bond strength of zirconia in different priming conditions. *Dent Mater*, 28(8):e127-e134. <https://doi.org/10.1016/j.dental.2012.04.020>
- Chintapalli RK, Marro FG, Jimenez-Pique E, et al., 2013. Phase transformation and subsurface damage in 3Y-TZP after sandblasting. *Dent Mater*, 29(5):566-572. <https://doi.org/10.1016/j.dental.2013.03.005>
- Feng Z, Qi JQ, Huang ZY, et al., 2017. Optimization of the amount and molecular weight of dispersing agent PEG during the co-precipitation preparation of nano-crystalline C-YSZ powder. *J Nanosci Nanotechnol*, 17(4):2613-2619.
- Fonseca RG, de Oliveira Abi-Rached F, dos Santos Nunes Reis JM, et al., 2013. Effect of particle size on the flexural strength and phase transformation of an airborne-particle abraded yttria-stabilized tetragonal zirconia polycrystal ceramic. *J Prosthet Dent*, 110(6):510-514. <https://doi.org/10.1016/j.prosdent.2013.07.007>
- Gans A, Dressaire E, Colnet B, et al., 2019. Dip-coating of suspensions. *Soft Matter*, 15(2):252-261. <https://doi.org/10.1039/c8sm01785a>
- Go EJ, Shin Y, Park JW, 2019. Evaluation of the microshear bond strength of MDP-containing and non-MDP-containing self-adhesive resin cement on zirconia restoration. *Oper Dent*, 44(4):379-385. <https://doi.org/10.2341/18-132-L>
- Karthigeyan S, Ravindran AJ, Bhat RTR, et al., 2019. Surface modification techniques for zirconia-based bioceramics: a review. *J Pharm Bioallied Sci*, 11(S2):S131-S134. https://doi.org/10.4103/JPBS.JPBS_45_19
- Kern M, 2015. Bonding to oxide ceramics—laboratory testing versus clinical outcome. *Dent Mater*, 31(1):8-14. <https://doi.org/10.1016/j.dental.2014.06.007>
- Keshvad A, Hakimanah SMR, 2018. Microtensile bond strength of a resin cement to silica-based and Y-TZP ceramics using different surface treatments. *J Prosthodont*, 27(1):67-74. <https://doi.org/10.1111/jopr.12622>
- Kim MJ, Kim YK, Kim KH, et al., 2011. Shear bond strengths of various luting cements to zirconia ceramic: surface chemical aspects. *J Dent*, 39(11):795-803. <https://doi.org/10.1016/j.jdent.2011.08.012>
- Lim MJ, Yu MK, Lee KW, 2018. The effect of continuous application of MDP-containing primer and luting resin cement on bond strength to tribochemical silica-coated Y-TZP. *Restor Dent Endod*, 43(2):e19. <https://doi.org/10.5395/rde.2018.43.e19>
- Lima RBW, Barreto SC, Alfrisy NM, et al., 2019. Effect of silane and MDP-based primers on physico-chemical properties of zirconia and its bond strength to resin cement. *Dent Mater*, 35(11):1557-1567. <https://doi.org/10.1016/j.dental.2019.07.008>

- Lung CYK, Liu D, Matinlinna JP, 2015. Silica coating of zirconia by silicon nitride hydrolysis on adhesion promotion of resin to zirconia. *Mater Sci Eng C Mater Biol Appl*, 46:103-110. <https://doi.org/10.1016/j.msec.2014.10.029>
- Madani A, Nakhaei M, Karami P, et al., 2016. Sol-gel dip coating of yttria-stabilized tetragonal zirconia dental ceramic by aluminosilicate nanocomposite as a novel technique to improve the bonding of veneering porcelain. *Int J Nanomedicine*, 11:3215-3223. <https://doi.org/10.2147/IJN.S104885>
- Mahmoodi N, Hooshmand T, Heidari S, et al., 2016. Effect of sandblasting, silica coating, and laser treatment on the microtensile bond strength of a dental zirconia ceramic to resin cements. *Lasers Med Sci*, 31(2):205-211. <https://doi.org/10.1007/s10103-015-1848-9>
- Mo LX, Guo ZX, Yang L, et al., 2019. Silver nanoparticles based ink with moderate sintering in flexible and printed electronics. *Int J Mol Sci*, 20(9):2124. <https://doi.org/10.3390/ijms20092124>
- Nagaoka N, Yoshihara K, Tamada Y, et al., 2019. Ultrastructure and bonding properties of tribochemical silica-coated zirconia. *Dent Mater J*, 38(1):107-113. <https://doi.org/10.4012/dmj.2017-397>
- Nassar HM, González-Cabezas C, 2011. Effect of gap geometry on secondary caries wall lesion development. *Caries Res*, 45(4):346-352. <https://doi.org/10.1159/000329384>
- Nishigawa G, Maruo Y, Irie M, et al., 2008. Ultrasonic cleaning of silica-coated zirconia influences bond strength between zirconia and resin luting material. *Dent Mater J*, 27(6):842-848. <https://doi.org/10.4012/dmj.27.842>
- Özcan M, Bernasconi M, 2015. Adhesion to zirconia used for dental restorations: a systematic review and meta-analysis. *J Adhes Dent*, 17(1):7-26. <https://doi.org/10.3290/j.jad.a33525>
- Park C, Park SW, Yun KD, et al., 2018. Effect of plasma treatment and its post process duration on shear bonding strength and antibacterial effect of dental zirconia. *Materials (Basel)*, 11(11):2233. <https://doi.org/10.3390/ma11112233>
- Phark JH, Duarte S, Blatz M, et al., 2009a. An in vitro evaluation of the long-term resin bond to a new densely sintered high-purity zirconium-oxide ceramic surface. *J Prosthet Dent*, 101(1):29-38. [https://doi.org/10.1016/S0022-3913\(08\)60286-3](https://doi.org/10.1016/S0022-3913(08)60286-3)
- Phark JH, Duarte S, Kahn H, et al., 2009b. Influence of contamination and cleaning on bond strength to modified zirconia. *Dent Mater*, 25(12):1541-1550. <https://doi.org/10.1016/j.dental.2009.07.007>
- Queiroz JRC, Benetti P, Massi M, et al., 2012. Effect of multiple firing and silica deposition on the zirconia-porcelain interfacial bond strength. *Dent Mater*, 28(7):763-768. <https://doi.org/10.1016/j.dental.2012.03.014>
- Ruales-Carrera E, Cesar PF, Henriques B, et al., 2019. Adhesion behavior of conventional and high-translucent zirconia: effect of surface conditioning methods and aging using an experimental methodology. *J Esthet Restor Dent*, 31(4):388-397. <https://doi.org/10.1111/jerd.12490>
- Saleh NE, Guven MC, Yildirim G, et al., 2019. Effect of different surface treatments and ceramic primers on shear bond strength of self-adhesive resin cement to zirconia ceramic. *Niger J Clin Pract*, 22(3):335-341. https://doi.org/10.4103/njcp.njcp_394_18
- Salem R, Naggar GE, Aboushelib M, et al., 2016. Microtensile bond strength of resin-bonded hightranslucency zirconia using different surface treatments. *J Adhes Dent*, 18(3):191-196. <https://doi.org/10.3290/j.jad.a36034>
- Tabatabaian F, 2019. Color aspect of monolithic zirconia restorations: a review of the literature. *J Prosthodont*, 28(3):276-287. <https://doi.org/10.1111/jopr.12906>
- Thammajaruk P, Inokoshi M, Chong S, et al., 2018. Bonding of composite cements to zirconia: a systematic review and meta-analysis of in vitro studies. *J Mech Behav Biomed Mater*, 80:258-268. <https://doi.org/10.1016/j.jmbbm.2018.02.008>
- Wille S, Lehmann F, Kern M, 2017. Durability of resin bonding to lithium disilicate and zirconia ceramic using a self-etching primer. *J Adhes Dent*, 19(6):491-496. <https://doi.org/10.3290/j.jad.a39545>
- Xie HF, Tay FR, Zhang FM, et al., 2015. Coupling of 10-methacryloyloxydecylidihydrogenphosphate to tetragonal zirconia: effect of pH reaction conditions on coordinate bonding. *Dent Mater*, 31(10):e218-e225. <https://doi.org/10.1016/j.dental.2015.06.014>
- Xu L, Liang HW, Yang Y, et al., 2018. Stability and reactivity: positive and negative aspects for nanoparticle processing. *Chem Rev*, 118(7):3209-3250. <https://doi.org/10.1021/acs.chemrev.7b00208>
- Zhao P, Yu P, Xiong YH, et al., 2020. Does the bond strength of highly translucent zirconia show a different dependence on the airborne-particle abrasion parameters in comparison to conventional zirconia? *J Prosthodont Res*, 64(1):60-70. <https://doi.org/10.1016/j.jpor.2019.04.008>