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RESEARCH AND EDUCATION

Influence of silane and 10-MDP in universal adhesives on bonding efficacy and chemical interaction with zirconia

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ABSTRACT

Statement of problem. Although universal adhesives have been widely used, the role of silane in their formulations, especially regarding its chemical stability and interaction with functional monomers like 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP), and how these factors affect zirconia bonding remains unclear.

Purpose. The purpose of this in vitro study was to investigate the effect of universal adhesives (UAs) on the microshear bond strength (μSBS) and chemical interaction to zirconia immediately (IM) and after thermal aging (TC).

Material and methods. Zirconia polycrystals were sectioned into blocks (n=96), cut into segments, and sintered. The segments were randomly assigned to 7 experimental groups (n=10) according to the following independent variables: adhesive treatment, categorized by the presence of silane, as follows: silane-free adhesives: Ambar (AMB) and Adper Single Bond 2 (SB2); silane/MDP containing adhesives: Ambar Universal APS (AMU), Scotchbond Universal (SBU); Ambar Universal APS Plus (AMU+), and Scotchbond Universal Plus (SBU+); and time: immediate (24 hours) or after 10 000 TC. Alloy Primer, a 10-MDP containing zirconia primer, was used as the positive control group. Additionally, 26 zirconia slices were subjected to micro-Raman spectroscopy to assess the chemical interaction after bonding procedures. After surface treatment, cylindrical molds were filled with resin cement and polymerized. All specimens were tested for μSBS at a crosshead speed of 1.0 mm/minute. Data were analyzed using the Kruskal-Wallis and Mann-Whitney tests (α=.05).

Results. At the immediate time, AMU, SBU, AMU+, and SBU+ exhibited μSBS values statistically comparable with those of Alloy Primer (P>.05), whereas AMB and SB2 showed significantly lower μSBS (P<.05). After TC, all groups demonstrated a significant decrease in μSBS (P<.001). Nevertheless, AMU, AMU+, SBU, and SBU+ preserved higher residual μSBS than the control group, while AMB and SB2 dropped to 0 MPa. Raman analysis confirmed chemical interaction between the adhesives (AMU, AMU+, SBU, and SBU+) and the zirconia surface.

Conclusions. The use of 10-MDP-containing universal adhesives was effective for zirconia bonding, enhancing the immediate performance and improving long-term durability. However, the inclusion of silane in these adhesives did not significantly influence the bond strength to zirconia. (J Prosthet Dent 2026;136:304-312)

Ceramic restorations have been widely used in dentistry to replicate the characteristics of dental tissues, making them a preferred choice among both professionals and patients,[1] and they have been increasingly recognized as high-strength materials for indirect dental restorations.[2] Advances in digital chairside milling technologies and innovative

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Clinical Implications

Silane-containing universal adhesives with 10-MDP did not impair zirconia bonding and performed similarly to a dedicated zirconia primer, indicating that universal adhesives may serve as a simplified and clinically effective option for zirconia bonding.

rapid-sintering techniques have rendered the fabrication of dental restorations more automated, efficient, and precise.[3–5] As a result, the use of ceramic materials, particularly zirconia, in dental prostheses has risen markedly.[6] Zirconia is a polycrystalline ceramic devoid of a glassy phase.[7] The addition of stabilizing oxides, such as yttrium oxide, to pure zirconia produces a multiphase material known as yttria-stabilized tetragonal zirconia polycrystal (Y-TPZ), distinguished by its superior physical properties, including high flexural strength, corrosion resistance, biocompatibility, and favorable optical characteristics.[8,9] Nevertheless, despite its numerous advantages, achieving reliable adhesive luting with zirconia continues to present a clinical challenge.[10,11]

Traditionally, resin bonding to glass-matrix ceramics has been achieved by etching the surface with hydrofluoric acid, which partially dissolves the glass phase and creates porosities for micromechanical retention, followed by the application of a silane coupling agent to establish chemical adhesion to silica.[12] Since zirconia lacks a glassy phase, hydrofluoric acid etching is considerably less effective on zirconia than on glass-matrix ceramics under comparable conditions.[13] Moreover, the absence of silica in zirconia limits the potential for chemical interaction with silane, rendering conventional silane treatments largely ineffective for zirconia bonding.[1,14] To address these limitations, several mechanical surface treatments have been proposed to enhance zirconia bonding effectiveness. Among them, airborne-particle abrasion with aluminum oxide (Al_2O_3) and silica-coated Al_2O_3 particles remain the most widely used and best-documented methods,[13,15] as they increase surface roughness and promote micromechanical interlocking with resin cements. Alternative approaches, such as laser irradiation,[16] selective infiltration etching,[17] airborne-particle abrasion with fluorapatite glass-ceramic[18] or glass beads,[19] have also been explored to modify surface energy and improve adhesive performance. These treatments are considered the most established methods of achieving reliable and durable bonding to zirconia ceramics. More recently, the use of zirconia primers has emerged as an option.[20–22] Zirconia primers incorporate functional monomers such as 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) with 2 functional groups: a phosphate group, which bonds to hydroxyl groups present on the zirconia surface, and a methacrylate group, which can be light-polymerized to form a strong link with resin cements, thereby enhancing bond strength.[23] Concomitantly, several manufacturers have developed 10-MDP-containing adhesives, known as universal adhesives.[24]

The term "universal" arises from the incorporation of acidic monomers such as 10-MDP,[25–27] which broadens the applicability of universal adhesives to include bonding with metal alloys, thereby eliminating the need for additional primers.[28,29] Furthermore, their use has been extended to other ceramics, including both glass-matrix and oxide-based ceramics, by incorporating silane into the formulation of universal adhesives.[30,31] However, silane-containing universal adhesives revealed limitations, as silane proved unstable owing to adverse interactions with 10-MDP.[32,33] Whether 10-MDP molecules undergo adverse reactions in the presence of silane, particularly when bonding to zirconia substrates, remains uncertain.[34–37] Some authors have suggested that the relatively high acidity (pH approximately 3.1) contributes to reduced bond strength to zirconia and to the hydrolytic degradation of silane in acidic environments.[38] In this way, the instability of silane can be attributed to the low pH of universal adhesives, which promotes the dehydration and self-condensation of silanol groups, resulting in a loss of reactivity over time.[39] This challenge prompted the introduction of so-called "universal adhesives plus," in which more stable silanol functionalities were developed. Nonetheless, as they are relatively newly introduced materials, studies evaluating their effectiveness in bonding to zirconia are sparse.[40] Since chemical bonding mechanisms and interactions between 10-MDP and silane are not fully understood, this can be a problem in terms of long-term bonding to the zirconia surface.[22]

The aim of this study, therefore, was to evaluate whether incorporating silane into universal adhesives influences bonding to zirconia ceramics. The null hypotheses were that different universal adhesive systems would not affect the bond strength between zirconia and resin cement, their immediate and post-thermocycling performance, and the chemical interaction between the adhesives and the zirconia surface.

MATERIAL AND METHODS

A total of 24 computer-aided design and computer-aided manufacturing (CAD-CAM) blocks of 5Y-TZP zirconia (Ceramill Zolid fx ML; Amann Girrbach AG) were sectioned into 96 specimens (diamond disc; Isomet, Buehler), ultrasonically cleaned, and sintered according to the manufacturer's instructions. Seventy specimens were randomly allocated (n=10 per group) into 7 bonding-treatment groups using a computer-generated sequence (Random.org) prepared by an independent researcher not involved in the experimental procedures. The groups were: bonding treatment: Alloy

Table 1. Materials, batch number, composition, and application modes

Material, Manufacturer, Batch Number	Composition	Application Mode
Ceramill Zolid FX ML Amann Girrbach AG # 943786	Type: 5Y-PSZ; $ZrO_2 + HfO_2 + Y_2O_3 \geq 99.0$ wt%	Sintering process: Heated to 1450 °C, held for 2 h, and cooled slowly to room temperature.
Alloy Primer Kuraray Noritake # 126546	10-MDP, VBATDT, Acetone	1. Apply with brush and let it dry.
Ambar (AMB) FGM Dental Group #300618 Silane free adhesive	Methacrylate monomers (UDMA and MDP), photoinitiators, co-initiators, stabilizers, inert silica nanoparticles, ethanol, photoinitiators, and stabilizers	1. Apply one coat of adhesive and brush for 20 s. 2. Gently air thin for 10 s to evaporate solvent. 3. Polymerize for 10 s at 1200 mW/cm^2.
Ambar Universal (AMU) FGM Dental Group #080622 MDP-containing adhesive	Methacrylate monomers (UDMA and 10-MDP), photoinitiators, coinitiators, stabilizers, inert silica nanoparticles and ethanol	1. Apply 2 coats vigorously by rubbing adhesive for 20 s (10 s each). 2. Gently air dried for 10 s to evaporate the solvent. 3. Polymerize for 10 s at 1200 mW/cm^2.
Ambar Universal APS Plus (AMU+) FGM Dental Group #030425 MDP/Silane containing adhesive	2-hydroxy-1,3-propanediyl bismethacrylate, Urethane dimethacrylate, 2-, HEMA, 10-MDP, silane, ethanol, water and	1. Apply and rub it in for 20 s. 2. Gentle air thin for minimum of 5 s. 3. Polymerize for 10 s at 1200 mW/cm^2.
Adper Single Bond 2 (SB2) Solventum #2110500653 MDP/Silane free adhesive	HEMA, Bis-GMA, dimethacrylate, methacrylate functional copolymer of polyacrylic and polyitaconic acid, ethanol, water, photoinitiator	1. Apply 2 consecutive coats of the adhesive with a fully saturated brush tip. 2. Gentle air thin for 5 s. 3. Polymerize 10 s at 1200 mW/cm^2.
Scotchbond Universal (SBU) Solventum #2417600159 MDP - containing adhesive	10-MDP, dimethacrylate resins, HEMA, methacrylate modified polyalkenoic acid copolymer, nanofiller, ethanol, water, initiators, silane	1. Apply and rub in for 20 s. 2. Gentle air thin for minimum of 5 s. 3. Polymerize for 10 s at 1200 mW/cm^2.
Scotchbond Universal Plus (SBU+); Solventum #9020296 MDP/Silane containing adhesive	Brominated dimethacrylate, HEMA, phosphorylated methacrylate, ethyl alcohol, silane treated silica, water, polymeric acid, camphorquinone, aromatic amine	1. Apply and rub in for 20 s. 2. Gentle air thin for minimum of 5 s. 3. Polymerize for 10 s at 1200 mW/cm^2.

10-MDP, 10-methacryloyloxydecyl dihydrogen phosphate; Bis-GMA, bisphenol A-glycydil methacrylate; HEMA, 2-hydroxyethyl methacrylate; UDMA, urethane methacrylate; VBATDT, 6-[4-ethenylphenyl-(n-propyl)] amino-1,3,5-triazine-2,4-dithione.

* Materials applied according to recommendations of their respective manufacturers.

Primer (control), Ambar (AMB), Ambar Universal APS (AMU), Ambar Universal APS Plus (AMB+), Adper Single Bond 2 (SB2), Scotchbond Universal (SBU), and Scotchbond Universal Plus (SBU+) and storage time: 24 hours or after 10 000 thermocycles (TC). Additionally, 26 zirconia slices were assigned to 8 experimental conditions (zirconia only [negative control], Alloy Primer [positive control], AMB, AMU, AMB+, SB2, SBU, and SBU+) for chemical interaction analyses. The composition and application protocol of all bonding agents are detailed in Table 1.

All specimens were embedded in acrylic-filled polyvinyl chloride rings (Vipi Flash; Vipi Industria), polished (#800 to #1200 grit; K2000 Polishing Paper; Exact), ultrasonically cleaned, and treated according to each manufacturer's instructions (Table 1). All bonding procedures were performed by a single operator (TCS).[28] Fourteen Tygon tubes (0.8×0.5 mm; Odeme Dental Research) were positioned on each zirconia surface, filled with resin cement (Calibra Ceram; Dentsply Sirona) (Table 1), and light polymerized for 40 seconds using a light-emitted diode unit (1200 mW/cm^2 Bluephase N; Ivoclar AG). Light output was regularly verified with a radiometer (Demetron L.E.D. Radiometer; Kerr Corp). All procedures were performed using ×10 magnification loupes.[38–42]

After 24 hours in distilled water at 37 °C, the tubes were removed, and defective specimens were discarded after examination under ×10 magnification. Half of the specimens were tested immediately; the remainder underwent 10 000 thermal cycles (5 °C to 55 °C; 1-minute dwell). Microshear bond strength (µSBS) was performed using a universal testing machine (Instron) with a 0.2-mm orthodontic wire loop around each resin cement cylinder and aligned with the bonding interface.[41] Testing was performed at 1 mm/minute until failure, and µSBS (MPa) was calculated by dividing the failure load by the area of the bonded interface. After testing, all specimens were examined under an optical microscope (SZH-131; Olympus Ltd) at ×100 magnification to determine the failure mode. Failures were classified as adhesive/mixed, cohesive in resin cement, or cohesive in zirconia.[38,41] Premature failures (PFs) occurring before testing were also recorded. A PF was defined as a specimen showing porosities or other defects under ×50 magnification or one that fractured spontaneously during testing.[38,41]

For the chemical interaction analysis, 3 zirconia sections per group were analyzed immediately after surface treatment using a micro-Raman spectrometer (LabRAM HR Evolution; Horiba Scientific). The instrumental was calibrated with a silicon standard (520.7 cm^{-1}), and spectra were collected by following the parameters of Gutierrez et al.[38] A ×50 long-working-distance objective (Olympus Ltd) and a 100-µm confocal aperture were used to record a spectral range of 100 to 1800 cm^{-1}. Baseline spectra were first obtained from untreated zirconia. Each primer or adhesive was then applied according to the manufacturer's instructions (Table 1), after which the specimens were rinsed with

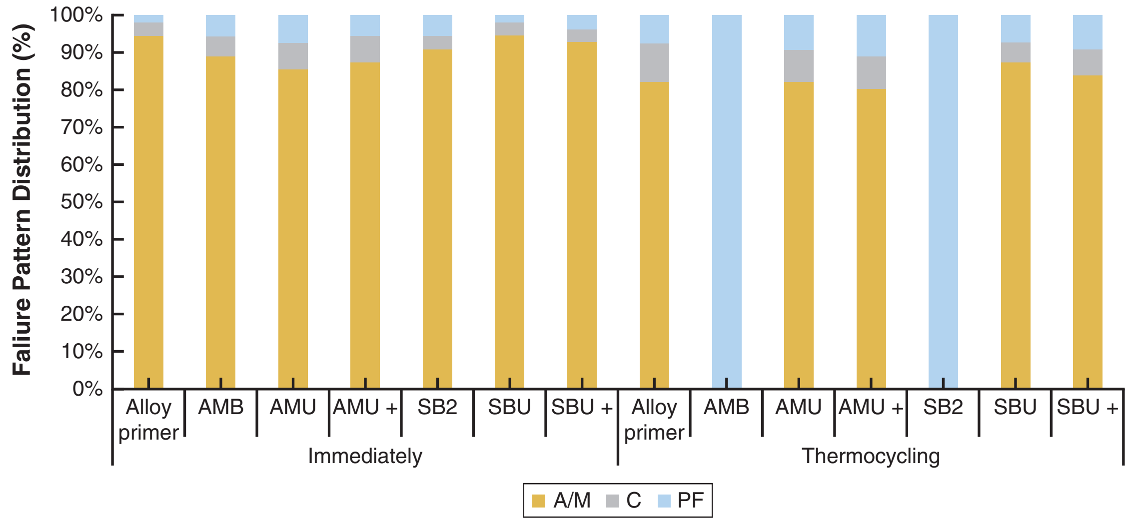

Figure 1. Graphical presentation of proportional prevalence of fracture mode for all experimental groups.

distilled water and absolute ethanol (30 seconds each) to remove unreacted or physically adsorbed material. Raman spectra were acquired in triplicate from areas randomly selected on each specimen using a computer-generated allocation sequence (Random.org) prepared by an independent researcher not involved in the experimental procedures.

Qualitative analysis was performed by spectral subtraction and comparison with reference peaks to identify phosphate-related vibrational bands (approximately 1040 to 1080 cm^{-1}) and shifts in Zr-O lattice (approximately 147 to 270 cm^{-1}), indicative of chemical interaction between functional monomers and zirconia.[38]

Sample size calculation was performed using an online tool (sealedenvelope.com) based on the µSBS values of Scotchbond Universal bonded to zirconia reported in the literature.[38] The expected mean and standard deviation were set at 24.7 ±2.6 MPa. With an alpha level of.05, an 80% power, and a minimum detectable difference of 5.1 MPa, the required sample size was 10 zirconia surfaces per group. For statistical analysis, the mean µSBS (MPa) of resin-zirconia bonded cylinders from the same zirconia surface at each evaluation period was averaged; therefore, the zirconia surface served as the experimental unit. After confirming normal distribution (Kolmogorov-Smirnov test) and homogeneity of variances (Bartlett test), the µSBS (MPa) values were statistically evaluated with a 2-way ANOVA (treatment versus time), followed by the Bonferroni post hoc test. All analyses were performed with a statistical software program (Statistica; StatSoft) (α=.05).

RESULTS

The percentage of premature failures and fracture pattern distribution are shown in Figure 1 and Table 2. Fifty-six bonded cylinders were tested for each experimental group. No specimens were discarded because of porosities or other defects, and no pretest failures were observed. The most frequent failure mode was adhesive/mixed failures (75.1% of all specimens), followed by premature failure (19.5%) and cohesive failure (5.4%).

In the immediate condition, only the universal adhesives (AMU, AMU+, SBU, and SBU+) demonstrated µSBS values statistically similar to those of the control group (Alloy Primer; P>.05) (Fig. 2). Silane-free adhesives presented significantly lower µSBS values compared with all other groups (P<.001) (Fig. 2, Table 2). When both evaluation times were compared, significantly lower µSBS values were observed after thermocycling (P<.001) (Table 2). Additionally, after thermocycling, a statistically significant difference among adhesives was detected (P=.001) (Fig. 2,

Table 2. Microshear bond strength means ±standard deviations (MPa) and number of specimens according to fracture mode

Experimental Groups	Time	
	Immediately	Thermally Aged
Alloy Primer (Control)	33.1 ±5.2 [53/2/1/56]	21.2 ±4.2 [46/6/4/56]
Ambar (AMB)	22.9 ±3.3 [50/3/3/56]	0.0 ±0.0 [0/0/56/56]
Ambar Universal APS (AMU)	34.3 ±2.9 [48/4/4/56]	25.2 ±3.1 [46/5/5/56]
Ambar Universal APS Plus (AMU+)	37.8 ±3.7 [49/4/3/56]	27.9 ±3.8 [45/5/6/56]
Adper Single Bond 2 (SB2)	24.8 ±4.9 [51/2/3/56]	0.0 ±0.0 [0/0/56/56]
Scotchbond Universal (SBU)	34.6 ±2.2 [53/2/1/56]	24.2 ±3.2 [49/3/4/56]
Scotchbond Universal Plus (SBU+)	35.6 ±4.9 [52/2/2/56]	24.3 ±3.9 [47/4/5/56]

Zirconia surface considered statistical unit (n=10/group). Number between square brackets represent the number of specimens (cement cylinders) following fracture mode classification [1/2/3/4]: (1) Adhesive/mixed failure; (2) Cohesive failure; (3) pre-test failure; (4) total number of tested specimens.

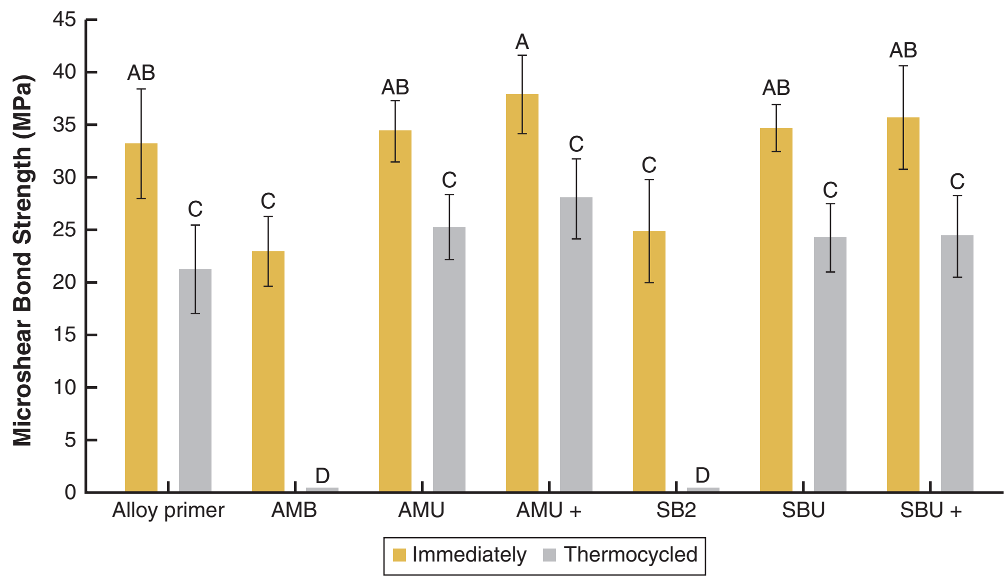

Figure 2. Mean microshear bond strength (MPa) and standard deviations for Alloy primer, Ambar (AMB), Ambar Universal APS (AMU), Ambar Universal APS Plus (AMU+), Adper Single Bond 2 (SB2), Scotchbond Universal (SBU), and Scotchbond Universal Plus (SBU+) on zirconia surface. Bond strengths assessed after 24 h and after 10 000 thermocycles. Different uppercase letters indicate statistically significant difference between groups (*P*<.001).

Table 2). Universal adhesives (AMU, AMU+, SBU, and SBU+) exhibited significantly higher µSBS values than both the control group and the silane-free adhesives (*P*<.001) (Table 2). Specimens from the AMB and SB2 groups did not survive the thermocycling procedure, resulting in no measurable µSBS values (Fig. 2, Table 2).

Representative micro-Raman spectra of the yttria-tetragonal polycrystal zirconia after different surface treatments are shown in Figure 3. The zirconia specimens were identified by the characteristic peaks of the ZrO_2 groups (267 cm^{-1}, 335 cm^{-1}, 476 cm^{-1}, and 637 cm^{-1}), which were observed in all spectra. In terms of chemical interaction, the Alloy Primer presented a more pronounced interaction pattern with the zirconia surface, as qualitatively indicated by the reduced intensity of zirconia-related peaks after surface treatment (Fig. 3). Similarly, the universal adhesives (SBU, AMU, SBU+, and AMB+) also exhibited noticeable interaction with zirconia, showing only minor reductions in these peak intensities.

DISCUSSION

In the present study, the µSBS test was used to evaluate the potential of silane and 10-MDP-containing universal adhesives for bonding to Y-TZP ceramics compared with 2-step etch-and-rinse adhesives (2-ERAs) and a silane-free 10-MDP-based primer, both immediately and after thermal aging. Although airborne-particle abrasion with alumina has been widely recognized as one of the most effective methods of improving zirconia bonding,[11] this procedure can induce a tetragonal-to-monoclinic phase transformation in Y-TZP ceramics, potentially compromising their mechanical integrity and long-term durability.[9] To specifically isolate and evaluate the effect of chemical interaction on bond strength and to eliminate confounding factors associated with surface roughness or residual stresses, no airborne-particle abrasion or other mechanical surface pretreatments were performed in this study.[21,29,31,42] Another important aspect of this study was that resin cement light polymerization was performed through the ceramic. Light attenuation caused by Y-TPZ, which exhibits varying degrees of translucency, can influence the polymerization and properties of the resin cement.[42–45] Previous studies have shown that the interposition of ceramic materials between the light source and the resin cement has reduced the degree of conversion and hardness, depending on ceramic thickness and light transmittance.[44] Therefore, the present methodology aimed to better simulate clinical conditions. Nonetheless, factors such as the type of resin cement, polymerization protocol, and light-polymerization device can significantly affect bonding outcomes,[46,47] and variations in these parameters may lead to different results.

The treated zirconia surfaces were bonded directly to the resin cement to address variations in adhesive composition, especially regarding acidity (pH), the presence of functional monomers, and solvent content, that may lead to chemical incompatibilities with resin cements, potentially affecting polymerization and long-term bond durability.[48] This methodology was chosen to determine the intrinsic behavior of the adhesive interface formed by these recently introduced universal

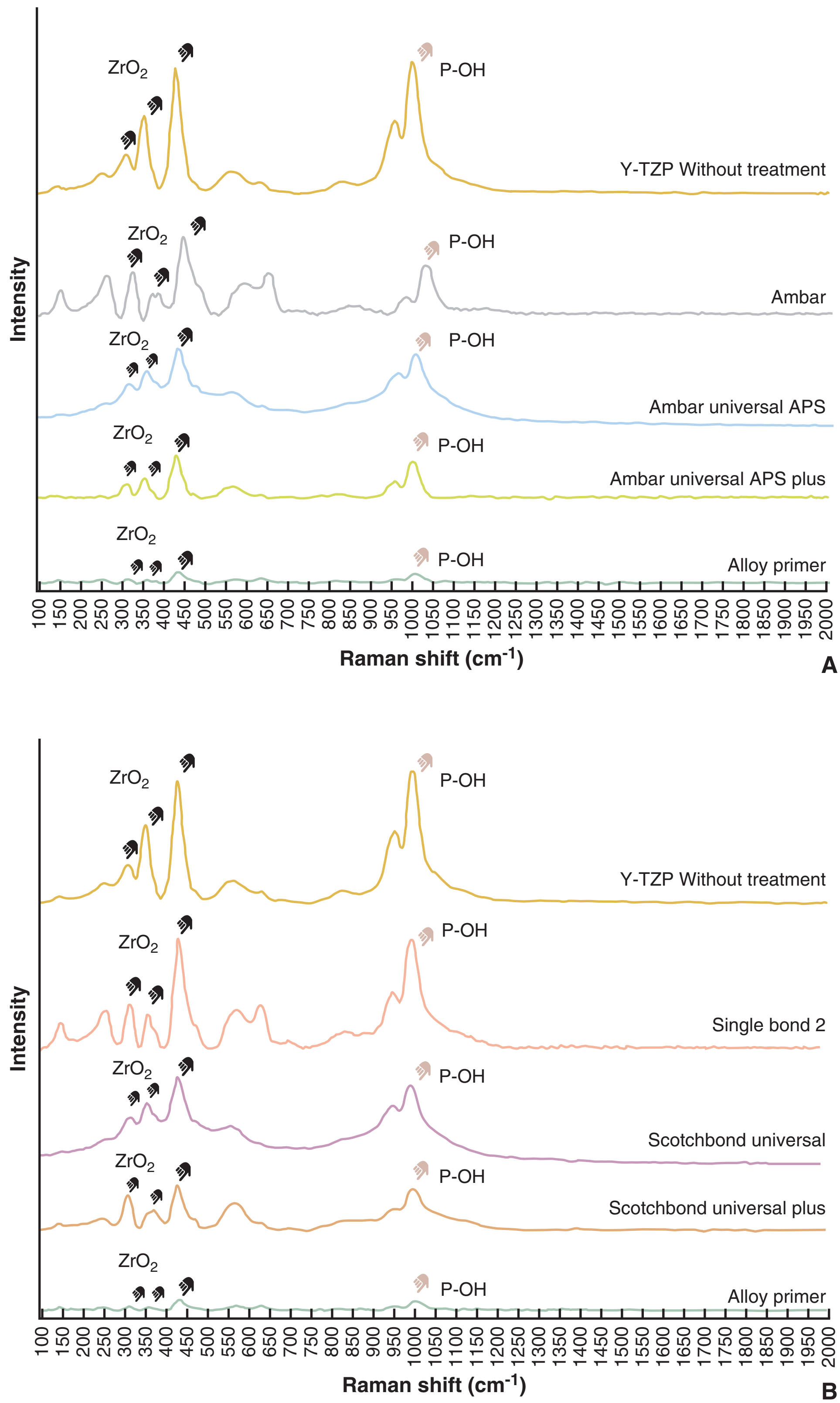

Figure 3. Chemical profile with representative micro-Raman spectra acquired on the Y-TZP surface after surfaces treatments and acetone rinsing. *Black hands* indicate regions corresponding to the tetragonal phase of zircon (310 to 440 cm^{-1}), while orange hands highlight phosphate groups (P-OH at 900 to 1100 cm^{-1}). A, Ambar, Ambar Universal APS and Ambar Universal APS Plus. B, Adpper Single bond 2, Scotchbond Universal and Scotchbond Universal Plus.

adhesives. The universal adhesives and the 10-MDP-based primer showed significantly higher bond strength and stronger chemical interaction with zirconia than 2-ERAs, leading to the rejection of the null hypotheses that different universal adhesive systems would not affect the bond strength between zirconia and resin cement, their immediate and post-thermocycling performance, and the chemical interaction between the adhesives and the zirconia surface. Historically, 2-ERAs were devolved to simplify bonding procedures when single-bottle adhesives became popular. However, they were not designed for bonding to substrates beyond enamel and dentin,[26] as the absence of functional monomers limited their performance on ceramics.[27] This limitation was confirmed by the present μSBS results, where 2-ERAs showed the lowest immediate bond strength, and, after thermal aging, no specimens survived. Moreover, no evidence of chemical interaction with the Y-TZP surface was observed (Fig. 3A, B). By contrast, the better performance observed in the universal adhesives and primer groups was attributed to the presence of 10-MDP.

The 10-MDP molecule consists of a phosphate group at one end and a vinyl group at the other, separated by a 10-carbon spacer chain.[33] The vinyl group promotes polymerization and interaction with the resin matrix, while the phosphate group is primarily responsible for bonding to hydroxyapatite and metal oxides such as zirconia.[33] This chemical interaction was confirmed in the present study, as evidenced by increased μSBS values in the 10-MDP-based primer group, along with characteristic shifts in zirconia peaks (260 cm^{-1}, 320 cm^{-1}, and 640 cm^{-1}) and phosphate group vibrations (νP-OH at 900 to 1100 cm^{-1}). The position and intensity of these peaks were directly associated with the chemical interaction between the 10-MDP molecule and zirconia.[38] During this process, the phosphate groups of 10-MDP lose hydroxyls to form direct bonds with Zr^{4+} ions, leading to a reduction in the intensity of the P-OH peak (900 to 1100 cm^{-1}), thereby characterizing the chemical interaction with the zirconia surface[38] as observed in the present study.

Universal adhesives also achieved strong bond strengths and chemical interaction with zirconia. Their role in zirconia bonding has been debated, with some studies supporting their efficacy[34,38] while others suggest they may not ensure long-term stability.[36] A key issue has been the addition of silane to universal adhesives, intended to enhance versatility across substrates. However, silane may interfere with 10-MDP function, reducing its absorption on zirconia.[36] In the present study, no significant difference in μSBS or chemical interaction was observed between universal adhesives, regardless of the presence of silane, and the silane-free primer, either immediately or after thermal aging. One of the negative effects of silane on the functionality of 10-MDP is the ability to dilute the concentration of 10-MDP, thereby impairing its absorption onto zirconia. However, these detrimental effects have been typically observed only when higher concentrations of silane are used.[35] Recently, Ye et al[35] have suggested that amounts of 5 or 10% silane do not produce a substantial diluting effect. The universal adhesives used in this study (SBU+ and AMB+) contain <0.5 wt% of silane in their composition. This amount of silane was probably not capable of considerably reducing the concentration of 10-MDP; this is supported by the chemical interaction analysis results for UAs, indicating that all universal adhesives could interact with the zirconia surface and suggesting that, even if some decrease in 10-MDP concentration occurred, it was minimal and insufficient to interfere with the chemical bond between 10-MDP and zirconia. Indeed, a recent systematic review and network meta-analysis reported that the concentration of 10-MDP present in primers and universal adhesives was sufficient to achieve effective chemical bonding to zirconia.[22]

Thermal aging did not result in statistically significant changes in μSBS values for either the primer or the universal adhesives, indicating stable bonding performance over time. This stability is primarily attributed to the formation of durable Zr-O-P covalent bonds between the phosphate group of 10-MDP and zirconium oxide, which are highly resistant to water sorption and hydrolytic degradation.[33] Additionally, the resin matrix in universal adhesives may act as a physical barrier that limits water penetration at the interface, protecting the chemical bonds formed between 10-MDP and zirconia.[38] The bifunctional structure of 10-MDP, comprising a phosphate group that anchors to zirconia and a methacrylate group that copolymerizes with the resin cement, creates a chemically integrated and hydrolytically stable interface.[15] Moreover, the presence of silane may enhance surface wettability and copolymerization with adhesive monomers, further improving interfacial bonding.[37] Collectively, these mechanisms explain the better long-term durability of MDP-based adhesives compared with non-MDP systems, highlighting their clinical relevance for reliable zirconia bonding.

Limitations of this study included that only one type of Y-TZP ceramic was evaluated, which may limit the generalizability of the results to other zirconia compositions. In addition, mechanical surface treatments were not included, and the aging protocol was limited, which may affect the extrapolation of the findings to long-term clinical performance. Furthermore, as an in vitro investigation, this study does not fully reproduce the complex oral environment. Future research should assess the interaction of silane- and 10-MDP-containing universal adhesives with different zirconia materials, explore their combined use with mechanical surface treatments, and evaluate their performance on other clinically relevant substrates such as enamel, dentin, and glass-ceramics under more rigorous and extended aging conditions.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. 10-MDP-based universal adhesives provided strong and durable bonding to zirconia, and adding silane did not alter their performance under the tested conditions.
2. The confirmed chemical interaction between 10-MDP and zirconia highlights functional monomers as the primary contributors to long-lasting adhesion.

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