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Association of solvents improves selected properties of experimental dental adhesives

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Abstract: The aim of the study was to evaluate how the association of solvents (tetrahydrofuran [THF], dimethyl sulfoxide [DMSO], ethanol [ET] or acetone [ACT]) with experimental dental adhesives affects selected properties of experimental dental adhesives and dentin bond durability. Six adhesive combinations were prepared containing: 30 % ET, 30 % ACT, 30 % THF, 28 % ET + 2 % DMSO (ET+DMSO), 15 % ethanol + 15 % THF (ET+THF), or 28 % THF + 2 % DMSO (THF+DMSO). Thirty-six molars (n = 6) were cut to expose the coronary dentin, and were randomly divided according to the adhesives. They were restored, and then cut into resin-dentin sticks (1 mm^2), and stored in distilled water for 24 h or 6 months, until conducting the microtensile bond strength and nanoleakage tests. Other experiments performed with adhesives included viscosity assessment using a rheometer, and degree of conversion using Fourier-transform infrared spectroscopy (FTIR). The data were analyzed statistically using two-way ANOVA and Tukey's test ($p < 0.05$). The adhesive formulated exclusively with THF showed the highest viscosity, followed by ET+THF, which obtained the highest degree of conversion compared to ET, and THF alone. ET+DMSO obtained the highest 24-h and aged bond strengths ($p < 0.05$). ET+THF increased the nanoleakage slightly after 6 months, but attained the only gap-free adhesive interface among all the groups. The combination of alternative solvents, particularly THF, with conventional ones (ET) has improved chemical properties, and the dentin bonding of experimental simplified adhesives.

Keywords: Solvents; Dental Bonding; Ethanol.

Introduction

Dental adhesives contain hydrophilic and hydrophobic resin monomers dissolved in volatile solvents, conventionally ethanol, acetone and/or water.[1] Indeed, several studies have evaluated alternative solvents, and their bonding and physical-chemical features. It has been demonstrated that adhesive formulations undoubtedly interfere with adhesive system performance.[1] Adhesive resins must incorporate hydrophobic monomers of high molecular weight. However, certain hydrophilic components are also included for optimal adhesive penetration (organic and moist substrate) in dentin. The solvents are then incorporated to obtain the proper mixture of these different compounds.

Another role of these organic solvents is to displace residual water from etched surfaces.[2] Solvents also act as a carrier for adhesive resins, and can improve their penetration into micro retentions on the tooth surface, thereby favoring micromechanical interlocking, and overall adhesion to the tooth structure.[3] Moreover, the polymerization reaction of monomers depends on the type of solvent and its evaporation, considering that solvents inhibit free-radical polymerization of most dental resins only relatively.[2]

Tetrahydrofuran (THF) has been reported as a viable alternative solvent for model adhesive systems, owing to its advantageous volatile properties (intermediary vapor pressure between ethanol [ET] and acetone [ACT]).[4] The use of a solvent with such properties may improve the stability of an adhesive polymer in the hybrid layer. Further reports in the literature describe minor investigations that study dentin bond degradation related to THF-based adhesives over time, and appreciable research concerning the biological effects of THF.[4]

Recently, dimethyl sulfoxide (DMSO) was introduced in adhesive dentistry as a new multifunctional solvent, which has a polar (S = O) group and two hydrophobic methyl groups, and which is fully miscible in most solvents, and in hydrophilic and hydrophobic monomers. The compact size and amphiphilic nature of DMSO allow it to penetrate biological surfaces efficiently. This could make it the greatest currently known penetration enhancer.[5] DMSO is also one of the most versatile solvents in the biological sciences, given that it partially inactivates the endogenous enzyme activity of MMP-2 and MMP-9.[6]

The solvents evaluated in this study are not used on a large scale, since they present drawbacks of cytotoxicity and impurities. DMSO alone has minor biocompatibility issues, and THF may have excess hexanes, which has toxic impurities. The cost of these solvents is another issue, since they are more expensive[4,5] than those traditionally used, such as ACT and ET.

Although these innovative solvents may have many positive effects on the dentin bond, and on the physicochemical properties of dental adhesives,[4-6] their association with traditional ET, as opposed to their use individually, has never been investigated to our knowledge. Potential synergistic effects could ameliorate bond durability and selected properties of adhesive resins, such as viscosity, and degree of conversion. In fact, these solvents may even promote increased longevity of a clinical restoration. Thus, the aim of the present in vitro investigation was to evaluate the effects of solvent associations with experimental adhesives on selected physicochemical properties and on dentin bond integrity. The hypothesis of this study was that the association of DMSO and/or THF with ET improves the durability of restorations and the physicochemical properties of dental adhesives.

Methodology

Adhesive formulation

Six experimental adhesives of different solvent proportions (5 g of each adhesive) were prepared manually at 25ºC, 50% relative humidity, and in a controlled yellow-light room (Table 1). A base adhesive was prepared from component mixtures in order of viscosity: 20% bisphenol-A dimethacrylate ethoxylate (BisEMA); 15% 1,3-glycerol-dimethacrylate phosphate (GPDM); 20% 2-hydroxyethyl methacrylate (HEMA); and 15% by weight of deionized water, needed to correct ionization of the acid monomer. The photoinitiator system was composed of 1% ethyl-dimethylamino-benzoate (EDAB, tertiary amine), and 0.5% camphorquinone (CQ, photosensitive agent).

Thirty percent of the solvents were added to each experimental adhesive in different ratios (ACT, ET, THF or DMSO). The solvents were weighed on a high-precision analytical balance, both individually and in their associations. Six adhesive combinations were prepared containing 30 % ET, 30 % ACT, 30 %

Table 1. Detailed information of solvent contents in different adhesive resins.

Adhesive	Solvent
ET	30 % Ethanol
ACT	30 % Acetone
THF	30 % Tetrahydrofuran
ET+DMSO	28 % Ethanol +2 % dimethyl sulfoxide
ET+THF	15 % Ethanol + 15 % tetrahydrofuran
THF+DMSO	28 % Tetrahydrofuran + 2 % dimethyl sulfoxide

THF (THF), 28 % ET + 2 % DMSO (ET+DMSO), 15 % ET + 15 % THF (ET+THF), or 28 % THF + 2 % DMSO (THF+DMSO).[4] The study design was experimental, quantitative, and analytical, with independent variables related to the different aforementioned adhesive formulations, and with storage/survey periods.

Viscosity test

The six experimental adhesives and the base adhesive (solvent-free) blend were evaluated using a rheometer (RST-CPS, Brookfield, Lorch, Germany). Each sample (n = 6) received 1 mL of adhesive dispensed in a vertical position for 5 s before undergoing tension for 30 s. The parameters were 20ºC, 200 µm gap, oscillation mode with 1% tension and 1 Hz.[7] The adhesive was forced to extrude three times through a cylinder of preset dimensions under high pressure. The decrease in pressure measured in the cylinder provided the flow rate data of the fluid, based on which the viscosity was calculated (cP). The values were submitted to statistical analysis with one-way ANOVA and Tukey's test ($p < 0.05$).

Fourier-transform infrared spectroscopy (FTIR)

The experimental adhesives were dispensed directly into a bar-shaped metal matrix measuring 7 mm x 2 mm x 1 mm (Odeme Dental Research, Luzerna, Brazil). The solvents were not evaporated to enable assessing their effect on curing. A glass plate was placed on the mold to prevent solution waste, by reducing contact with atmospheric oxygen, and keeping the solvents from evaporating. The photo-activation was performed immediately using a Valo LED unit (1,200 mW/cm^2, Ultradent, South Jordan, USA) for 40 s. The specimens were positioned on a zinc selenide crystal (SeZn) of an attenuated total reflectance device of the FTIR spectrometer (Spectrum 100 Optica; Perkin Elmer, São Paulo, Brazil), Next, the C = C aliphatic (1,635 cm^{-1}) and the aromatic (1,608 cm^{-1}) peaks were registered after the baseline correction, and the degree (%) of conversion was calculated for each material. Experiments were performed in triplicate (n = 3) for each experimental adhesive. The values were subjected to one-way ANOVA statistical analysis and Tukey's test ($p < 0.05$).

Microtensile bond strength (µTBS)

Thirty-six extracted caries-free third molars were selected and sectioned 2 mm above the cementum-enamel junction, and 3 mm below it to expose the flat middle dentin for performing the adhesive procedures. The cuts were made in the Cut Master (Londrina, Brazil) metallographic cutting machine, with a slow-speed water-cooled diamond saw. Each exposed dentin surface was abraded with 320-grit silicon carbide paper for 30 s under running water, to obtain a standardized smear layer.[6] The teeth were randomly bonded with one of the experimental adhesives (n = 6).

The dentin surface was etched with 37 % phosphoric acid (Condac 37, FGM, Joinville, Brazil) for 15s, and washed for 30s. The etch-and-rinse experimental adhesives were applied for 30s, and dried slightly with an air jet for 5 s, after which a second layer was applied for another 30 s. Lastly, the adhesives were light-cured for 40s (Valo LED unit). Afterwards, build-ups were constructed with Opallis restorative composite (FGM) in two 2-mm-thick increments. The specimens were sectioned to obtain resin-dentin sticks of approximately 1 mm^2, and subsequently stored for 24h or 6 months immersed in distilled water at 37ºC. The sticks were glued to jigs, and positioned in a universal testing machine EMIC-Instron (Model 23-5S, São José dos Pinhais, Brazil). After fracture, the samples were carefully removed, and their cross-sectional area was measured with a digital caliper at 0.01 mm precision. The values were submitted to statistical analysis with two-way ANOVA (experimental adhesive and storage time) and Tukey's test ($p < 0.05$).

Failure pattern analysis

Subsequent to statistical fracture analysis, the failure pattern of each fractured stick was determined using an optical microscope at 60 x magnification (Olympus, London, UK). The fractures were then classified as adhesive, mixed, cohesive in composite, and cohesive in dentin.

Nanoleakage analysis

Three sticks from each bonded tooth were randomly selected (n = 18) and kept immersed in 50 % silver nitrate solution (AgNO3 [Ag]) in the dark, for 24 hours.[8] The specimens were rinsed with distilled water, then immersed in photo developing solution for 8 hours under direct light to reduce silver ions into metallic silver grains. The silver-impregnated sticks were embedded in epoxy resin and polished using 600- and 1200-grit SiC paper and diamond pastes (Buehler, Lake Bluff, USA) with particle sizes of 3, 1 and 0.25 µm, and were ultrasonically cleaned for 15 min after each abrasive/polishing step. The specimens were finally air-dried, dehydrated overnight in a vacuum incubator with silica gel, coated with carbon, and analyzed using a scanning electron microscope (JSM-5600LV, JEOL, Tokyo, Japan), in backscattered electron mode with standardized magnification.

Results

The rheological analysis showed that THF was the most viscous adhesive resin among the resins of all the groups, and was statistically similar to the solvent-free adhesive blend. ACT had the lowest viscosity (Figure 1). The results for the degree of conversion demonstrated that ET+THF had the highest percentage of monomers converted to polymer, similar only to ACT and THF+DMSO adhesives. The lowest degree of polymerization occurred with ET+DMSO (Figure 2).

ET+DMSO obtained the highest bond strength values, both immediately and after six months, and

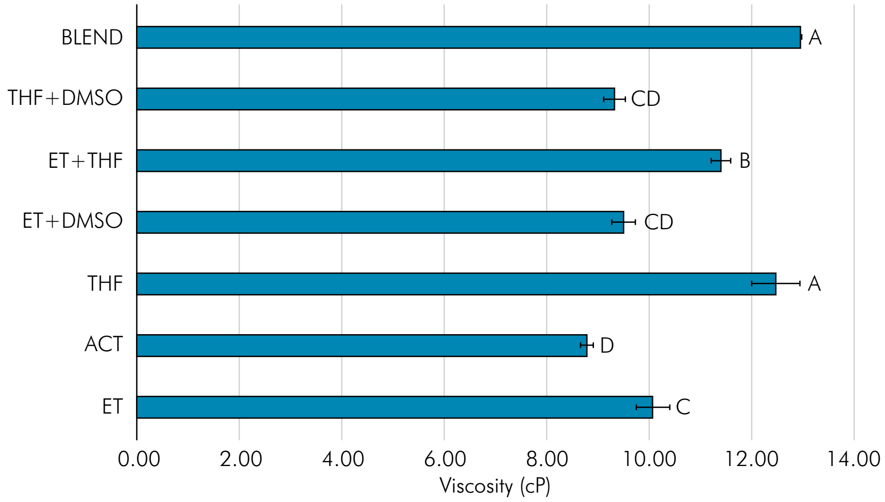

Figure 1. Results of viscosity analysis.

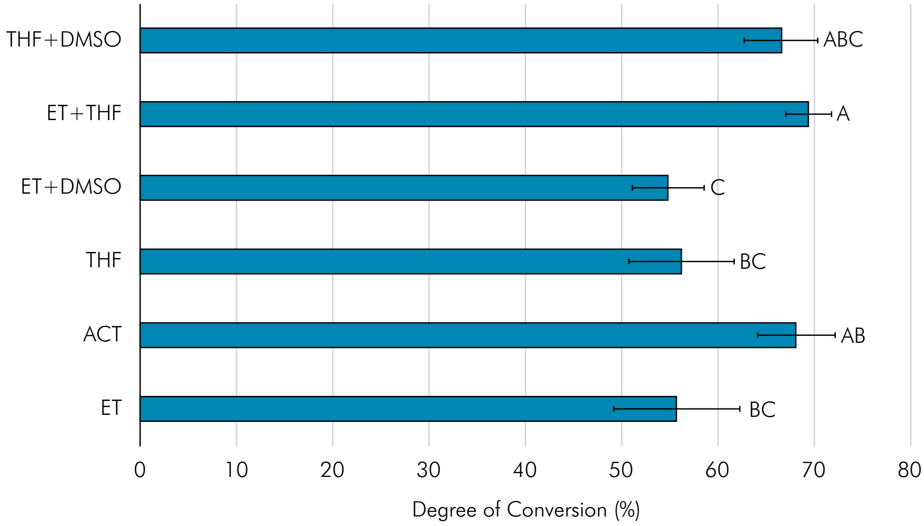

Figure 2. Outcomes of degree of conversion (%) researched by FTIR.

was similar only to THF+DMSO after 6 months. THF and ET+THF showed no statistical difference. ACT showed superior resistance to THF+DMSO in the immediate time point, but was similar to it after 6 months. However, ET obtained the lowest bond strength values both immediately and after 6 months. The results are shown in Table 2. The predominant failure pattern in all the groups was adhesive, as shown in Figure 3. The representative nanoleakage images after 24 h and 6 months are shown in Figure 4. The THF and ET+THF groups showed less silver impregnation in general, and the latter was the only one to achieve a gap-free interface.

Discussion

Based on the results observed, the hypothesis of this study was accepted. In the present investigation, simplified dental adhesives were used, containing solvents and different monomers in a single bottle. Solvents have an important role in promoting comonomer penetration in demineralized and wet dentin. Accordingly, different solvents are commonly experimented, and the mechanical and rheological properties may change.[9] The viscosity of the experimental adhesives is influenced by the Newtonian behavior of monomers, and the result of component interaction.[10] High viscosity

Table 2. Means (standard deviation) of microtensile bond strength (μTBS).

μTBS (MPa)	ET	ACT	THF	ET+DMSO	ET+THF	THF+DMSO
24 h	15.5(4.7) a,D	28.6(4.6) a,BC	33.3(5.1) a,B	47.1(4.6) a,A	33.7(3.7) a,B	21.1(5.5) b,CD
6 m	15.6(4.5)a,D	31.8(5.1) a,BC	23.8(4.7) b,CD	43.3(4.6) a, A	32.2(5.7) a,BC	38.4(5.7) a,AB

*Different uppercase letters in lines, and different lowercase letters in columns represent statistically significant difference ($p < 0.05$).

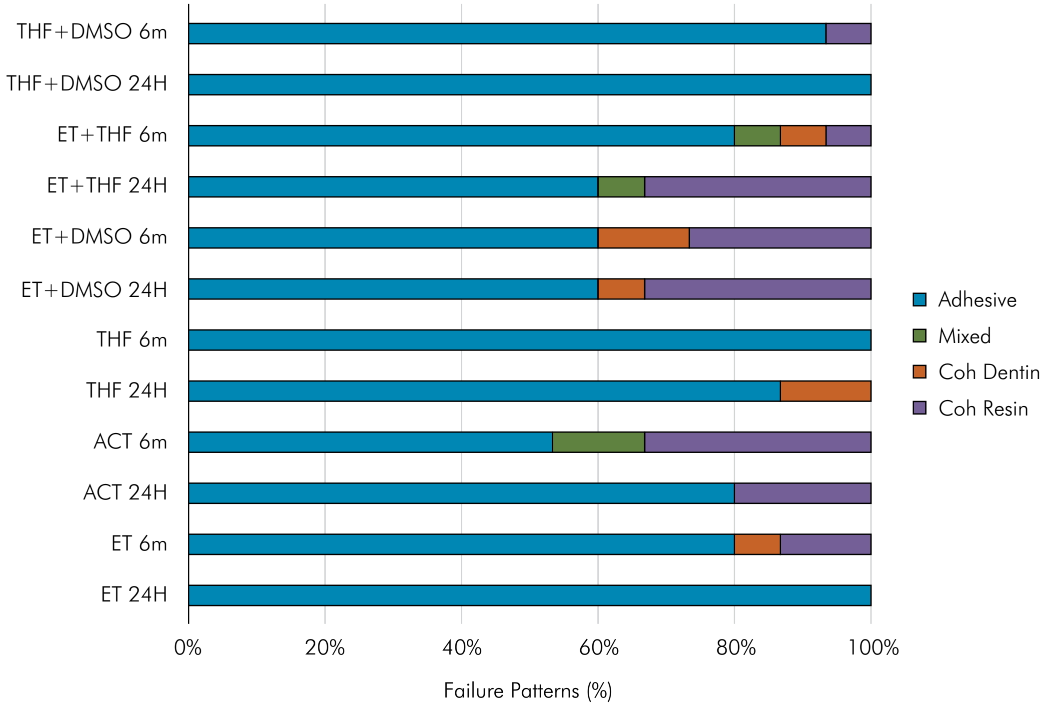

Figure 3. Outcomes of failure pattern analysis.

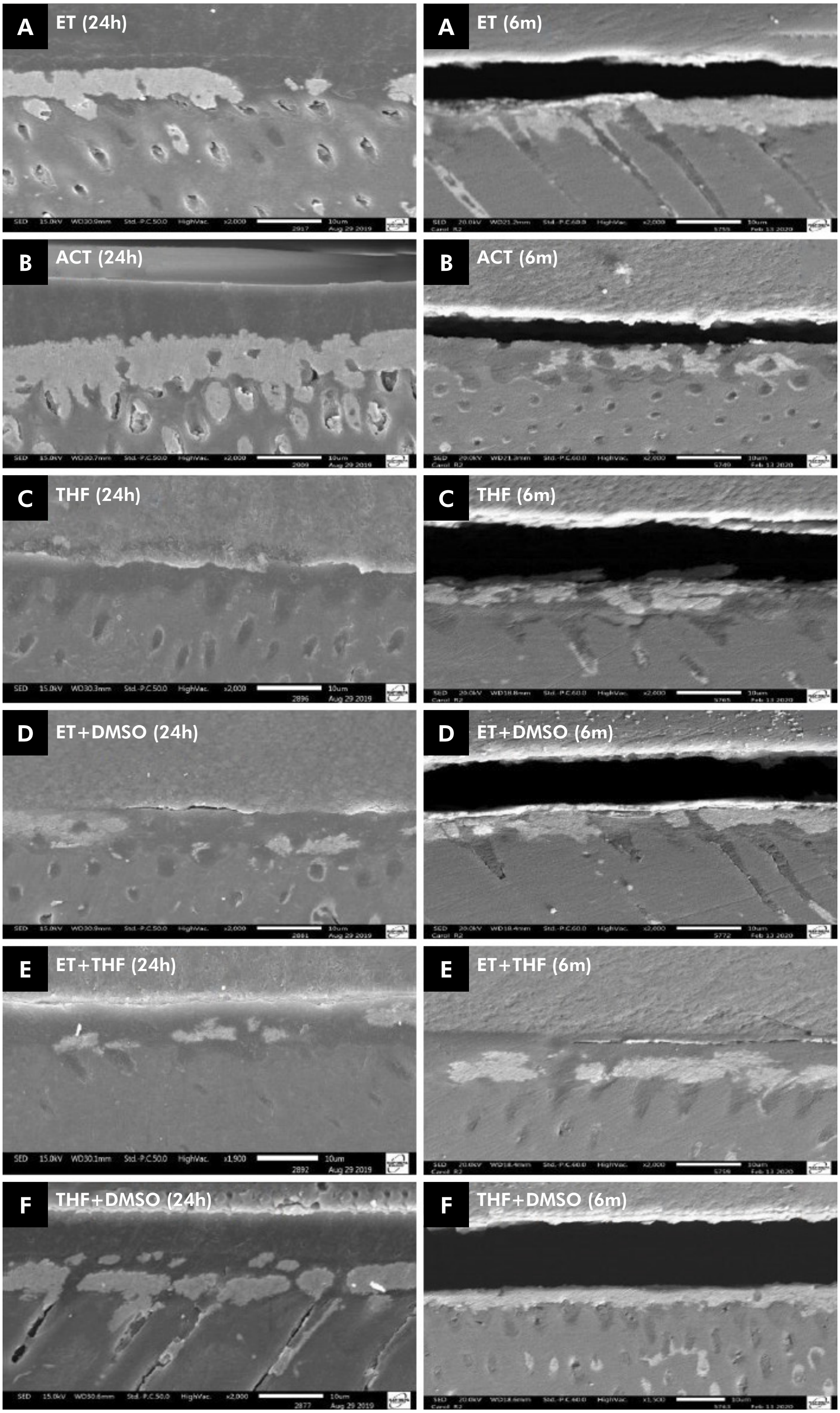

Figure 4. Representative SEM micrographs of silver nitrate impregnation (nanoleakage).

causes greater intermolecular interactions, which are related to a higher degree of conversion. This physicochemical feature indicates the resistance to flow, and is caused by intermolecular attraction. This property of the liquids results from internal friction, and cohesive forces between molecules; this resistance increases with molecular weight. Compounds that contain oxygen radicals, such as ET and THF, form hydrogen bonds.

Most likely, the ET formed hydrogen bonds with THF, and the intermolecular interaction hindered the movement of molecules, thereby increasing the liquid viscosity. The adhesive formulated with THF – an alicyclic ether – showed the highest viscosity, followed by its association with ET (ET+THF), as shown in Figure 1. The association of ET+THF benefited monomer polymerization, and was statistically superior to both of the other solvents used separately, as shown in Figure 2. Among the solvents, ACT showed the lowest viscosity, and its use was found to increase bond strength, likely due to its higher capacity to remove water, in comparison with ET.[11,12]

The water and hydrophilic solvents in adhesive systems prevent the organic matrix from stiffening, and favor resin monomer infiltration.[12] However, after fulfilling their role, solvents require volatilization to avert polymerization inhibition.[2,3] The adhesive with the highest degree of conversion was the ET+THF combination, with both polar solvents; however, there was no significant difference between this combination and THF+DMSO or ACT-containing adhesive (Figure 2). Solvents such as ACT may contract the collagen matrix, thereby decreasing resin monomer infiltration.[13] ACT has the highest vapor pressure among the solvents tested, hence promoting increased volatilization and a higher degree of conversion.[9,14]

The ET+DMSO group achieved the highest bond strength at 24 h, and after 6 months storage (Table 2). DMSO has low viscosity and evaporation rates. Its ability to combine with different types of substances allows it to re-expand the collapsed collagen network after excessive drying.[15] This collapse occurs in the interpeptide bond of demineralized collagen that may return to an optimal state for adhesive infiltration, if properly treated.[16] The greatest initial bonding of ET+DMSO and ET+THF resulted in a lower percentage of adhesive fractures compared to ET alone (Figure 3).

Regarding the type of solvent, each solvent has different characteristics related to vapor pressure, solubility pattern and hydrophilicity, and each different characteristic produces contrasting polymerization results.[12,13] The separate use of each solvent involves specific levels of vapor pressure and time periods to re-expand relatively dried collagen for polymeric matrix infiltration.[4] The association of THF and ET presented optimal results of dentin bonding and degree of conversion, and maintained the bond strength after 6-month aging.

The association of ET with alternative solvents, mainly THF, promoted bonding stability after 6 months, and less immediate silver impregnation, thereby causing fewer defects at the adhesive interface. Only ET+THF showed a high degree of conversion, bonding stability, and no gaps in the hybrid layer at either storage period. The interaction of DMSO with collagen decreased infiltration, and increased initial bonding. [5,6] The occurrence of nanoleakage at the resin-dentin interface, produced by etch-and-rinse adhesive systems, is difficult to avoid. Water infiltration affects the stability of resin-dentin bonding at different levels. Therefore, the development of strategies that promote a reliable bond to dentin substrate is crucial.[11] Conversely, the presence of a residual solvent along the adhesive interface could deteriorate the bond with the composite, creating gaps over time.[3,4,16]

The storage of restored specimens in water affects the stability of resin-dentin bonding at different levels. Therefore, the development of agents that promote reliable bond to dentin substrate is crucial.[11] Otherwise, the presence of a solvent along the adhesive interface may deteriorate the adhesive bond with the composite, and create gaps over time. ET is currently the most commonly used solvent. According to Delannee et al.[17] and Manhart et al.[18], many alternative solvents have been studied for their individual use, such as t-butanol, a solvent already found in commercial adhesive systems (XP Bond, two-step etch-and-rinse adhesive, and Xeno V, single-step self-etching, both from Dentsply). This solvent is more hydrophobic than ET and ACT; therefore, it is more suitable for dissolving hydrophobic monomers and promoting their infiltration in wet substrate. Several investigations have researched the role of THF and DMSO used individually, and have indicated satisfactory outcomes.[6,15,19] However, the present study was the first to show that the association of several different solvents promotes beneficial effects by increasing the positive effects of the solvents used alone.

Conclusion

DMSO + ETHANOL and THF + ETHANOL showed significant outcomes, in comparison with adhesive systems plus conventional solvents. As reported, the improvement of bond to dentin, and of the physicochemical features of the experimental adhesives is noteworthy. DMSO and THF may be useful as alternative solvents added to ethanol, to improve the long-term preservation of the bond strength to dentin, albeit clinical studies are still needed to prove their effectiveness.

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