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Laboratory Research

Interfacial Nanoleakage and Bonding of Self-Adhesive Systems Cured with a Modified-Layering Technique to Dentin of Weakened Roots

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Clinical Relevance

Self-adhering systems demonstrated better bonding to root dentin than self-etch systems. A modified-layering technique with high-intensity light-curing units can be recommended when restoring weakened roots with light-curable adhesive materials.

SUMMARY

Objective: The purpose of the study was to evaluate the nanoleakage and bond strength of different self adhesive systems cured with a modified-layering technique (MLT) to dentin of weakened roots.

Methods: Twenty-one maxillary incisors were decoronated and then root canals were instrumented and obturated with the cold lateral compaction technique. Weakened roots were simulated by flaring root canals until only 1 mm dentin thickness remained. Teeth were distributed into three groups. The canals were backfilled with Vertise Flow (VF group), a self-adhering system, following a modified-layering technique using two light-transmitting posts, sizes 6 and 3. DT Light Post size 2 was cemented using the same material. Remaining roots were prepared and cured in the same way as the VF group. However, in the TS/MF group, Clearfil Tri-S Bond (TS) adhesive and Clearfil Majesty Flow (MF) composite were used, while in the ED/PF group, ED primer II (ED)/Panavia F2.0 (PF) were used. After one week of storage, each root was sectioned to obtain six slices (two slices from each root third: coronal, middle and apical) of 0.9 ± 0.1 mm thickness. Interfacial nanoleakage expression was analyzed using a field emission scanning electron microscope (FEG-SEM), and the micro push-out

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bond strength (μPOBS) was measured at different root regions. Modes of failure were also determined using SEM. Data were statistically analyzed using two-way analysis of variance with repeated measures and Tukey *post hoc* test ($p \leq 0.05$).

Results: With MLT, all adhesive systems showed nanoleakage. For μPOBS, there was a statistically significant effect for adhesive systems ($p<0.001$) but not for root region ($p<0.64$) or for their interaction ($p=0.99$). Tukey *post hoc* test revealed that the bond strength of the VF group was significantly higher than the TS/MF and ED/PF groups for all root regions.

Conclusion: All of the tested self-adhesive systems cured using MLT had slight nanoleakage and were not sensitive to root regional differences. Self-adhering systems had higher bond strength than self-etch adhesives.

INTRODUCTION

In clinical situations, it is not uncommon for patients to suffer from vertical root fractures of endodontically treated teeth, even when the endodontic treatment has been successful.[1] Thus, thin dentinal walls due to instrumentation and post preparation of endodontically treated teeth remains a restorative problem. Therefore, when restoring such teeth, it would be advantageous to reinforce the roots aiming to increase their resistance to fracture. Researchers have tested the reinforcing effect of different materials, including glass ionomer cements, hybrids of glass ionomer cements, and resin composites with different post systems, including metal or fiber posts.[2-4] Fiber posts have further extended the applications of adhesive dentistry in endodontics and have been advocated because of their advantages of corrosion resistance, esthetic appeal, single-visit office placement, and easier removal for endodontic retreatment.[5] Additionally, fiber posts with resin composites that bond to dentin have surpassed other approaches in increasing the fracture resistance.[4] Nevertheless, the presence of multistep adhesives with technique sensitivity, the difficulty in material application, and curing effectiveness and the high C-factor (ratio of bonded to unbonded surfaces) in root canals make bonding to root dentin a real challenge.

In coronal restorations, to overcome the problems of multistep adhesives and their technique sensitivity, adhesive application steps were simplified ending up with the most recent single-step self-adhering resin composite.[6] Also, the use of a layering technique increased curing effectiveness,[7] decreased the volumetric shrinkage,[7,8] and decreased the C-factor.[9] Applying these approaches while restoring the root canal presents an attractive solution to manage the problem of bonding to weakened root canals.

The use of the new light-cured self-adhesive resin composites would allow for proper application and extend the working time for the restoration of weakened roots. In root canals, plastic light-transmitting posts and recently the newer versions of fiber post were developed to help in light transmission to increase the depth of resin cure.[10] However, it is accepted that light curing from the top of post spaces is insufficient to optimally polymerize light-curing adhesives and resin cements.[11-13] Whether the use of the light-transmitting posts in successive sizes to apply resin material in layers would lead to decreased volumetric shrinkage and C-factor while achieving effective curing leading to homogeneous bonding throughout the root dentin has not yet been investigated. For bonding behavior of the adhesives inside the canal, nanoleakage at the root dentin–adhesive interface was analyzed and bond strength measured. Simultaneous measurements of nanoleakage and bond strength were taken by many researchers to investigate the adhesive-dentin interface for coronal restorations,[14-17] whereas preparation for nanoleakage measurements prior to bond strength were proven to have no influence on bond strength.[18,19] Adoption of this approach while evaluating bonding to root dentin can be of value, as this would allow measuring bond strength and the evaluation of the sealing at the interface.[20]

Thus, the objective of this study was to examine the interfacial nanoleakage and regional push-out bond strength of different self-adhesive systems, cured with a modified-layering technique, to dentin of weakened roots. The null hypotheses tested were the following: 1) the tested adhesive systems cured with a modified-layering technique would not reveal significantly different micro push-out bond strengths (μPOBS) to root dentin, and 2) the micro push-out bond strengths of each tested adhesive system cured with the modified-layering technique would not be significantly different among root sections.

MATERIALS AND METHODS

Tooth Selection and Standardization

Intact human maxillary incisors were collected, cleaned, and disinfected and then stored in saline until use.[21] Root length and mesio-distal and bucco-lingual diameters at the cemento-enamel junction (CEJ) of the collected teeth were measured by digital caliper (Mitutoyo digital caliber, Mitutoyo Corp, Kawasaki, Japan).[3] Teeth (n=21) with similar root sizes and lengths were selected. The overall mean (range) root dimensions of all selected teeth measured at the CEJ were 5 ± 1 mm mesio-distally and 6 ± 1 mm bucco-lingually. The root length was approximately15 ± 1 mm.

Tooth Preparation and Weakened Root Simulation

The anatomical crowns of teeth were cut off perpendicular to the long axis of the roots, leaving 2 mm coronal to the CEJ of the buccal surfaces using a low-speed IsoMet saw (IsoMet, Lake Bluff, IL, USA) under water coolant. The root canals were instrumented using the step-back technique at a working length of 1 mm short of the apex to a master apical file size 60 K-file (Mani, Tochigi, Japan) using 2.5% NaOCl irrigation (Clorox, Egyptian Company for Household Products, 10th of Ramadan City, Egypt) and coronally flared using Gates Glidden drills sizes 2 and 3. The smear layer was removed with 3 ml 17% EDTA (Prevest Denpro Ltd, Jammu, India) for 1 min. Then the canals were dried with paper points (Diadent, Seoul, Korea) and filled with gutta-percha (Diadent) and AH Plus resin sealer (Dentsply DeTrey GmbH, Konstanz, Germany) using cold lateral compaction. After endodontic treatment, the teeth were sealed with Coltosol F temporary filling (Coltène/Whaledent AG, Altstätten, Switzerland) and stored at 37°C and 100% relative humidity for 48 hours.

Coronal gutta-percha was removed using Peeso reamers (size 2; Dentsply Maillefer, Ballaigues, Switzerland) to a depth of 12 mm, leaving about 4 ± 1 mm of obturating material apically. To simulate the weakened root canal walls, the canals were enlarged apically to a depth of 12 mm using Peeso reamers (Dentsply Maillefer) of ascending sizes from size 3 (1.1-mm diameter) to size 6 (1.7-mm diameter) in all teeth. The canal spaces were flared, leaving approximately 1 ± 0.2 mm of dentin thickness between the internal prepared root canal wall and the external root surface at the cervical region using high-speed tapered diamond burs (Dentsply Maillefer). The remaining thickness was confirmed with a digital caliper (Mitutoyo digital caliber, Mitutoyo Corp).[22] After flaring, bucco-lingual and mesio-distal radiographs were taken to ensure the homogeneity of root flaring. The roots were then centrally embedded in polyester (polyester #2121, Eternal Chemical Co., LTD, Hsien, Taiwan) along their long axis following the methodology described by Mobarak and others[23] In each canal, the smear layer was removed using 5 mL of 17% EDTA followed by 5 mL of 5.25% NaOCl as an irrigant. Final irrigation was accomplished with 10 mL of distilled water,[24] then air-dried with high-pressure airflow for five seconds.

Specimen Grouping

The embedded specimens (n=21) were then equally divided into three groups (n=7) according to the reinforcing materials used (Table 1) as follows:

VF Group—Seven flared specimens received Vertise Flow (VF) material (Kerr Corp, Orange, CA, USA), a light-cure self-adhering flowable resin composite, in three layering applications. A light coat of VF was first agitated onto the canal walls using a disposable microbrush applicator (Microbrush International Co, Grafton, WI, USA). A light-transmitting plastic post size 6 (Luminex, Dentatus USA Ltd, New York, NY, USA) was then inserted centrally in the root canal at the level of the apical gutta-percha, leaving circumferentially approximately 0.5 mm of thickness of VF resin composite material. Curing was done through the light-transmitting post for 80 seconds using Elipar S10 (3M ESPE Dental Products, St. Paul, MN, USA). The light-curing unit had an intensity ≥1400 mw/cm^2 and was checked using a radiometer (Kerr Corp). After curing, the light-transmitting plastic post was removed. A second layer of VF was then applied and cured with the aid of a size 3 light-transmitting plastic post (Luminex, Dentatus USA) to obtain a circumferential resin composite of thickness less than 2 mm. This layer was also cured for 80 seconds in the same way as the first layer. After curing, the light-transmitting post was removed. The remaining space was then filled with VF, then a DT Light Post (size 2, Bisco Inc, Schaumburg, IL, USA) was placed slowly and an additional 80 seconds curing applied.

TS/MF Group—Specimens (n=7) were filled as group 1, but the light-cure single-step self-etch adhesive system Clearfil Tri-S Bond and flowable resin composite Clearfil Majesty Flow (Kuraray Medical Inc, Tokyo, Japan) were used instead. Clearfil Tri-S Bond was applied according to the manufacturer's instructions. Light curing through size 6 light-transmitting plastic post for 80 seconds was done. The canals were then filled with Clearfil Majesty Flow using the other successive light-transmitting posts and finally the DT Light Post

Table 1: *Materials Descriptions, Manufacturers, Compositions, and Batch Numbers*

Material (Manufacturer)	Description	Composition and Batch Number
Clearfil Tri-S Bond (Kuraray Medical Inc, Tokyo, Japan)	Light cure Single-step self-etch adhesive system	MDP, Bis-GMA, HEMA, photoinitiators, ethanol, water, silanated colloidal silica (061232)
Clearfil Majesty Flow (Kuraray Medical Inc., Tokyo, Japan)	Light cure flowable resin composite	TEGDMA, silanated barium glass filler, silanated colloidal silica, hydrophobic aromatic dimethacrylate, di-camphorquinone (00308A)
Vertise Flow (Kerr Corp, Orange, C)	Light cure self-adhering flowable resin composite	Matrix: GPDM and methacrylate co-monomers Fillers: (70wt%): prepolymerized filler, barium glass, nanosized colloidal silica, nanosized ytterbium fluoride (3358782)
Panavia F2.0 (Kuraray Medical)	Dual-cure single-step self-etch resin cement	ED primer II Liquid A: HEMA (30-50%), MDP, *N*-methacryloyl-5-aminosalicylic acid, water, accelerator (61185). ED primer II Liquid B: N-methacryloyl-5-aminosalicylic acid, accelerator, water, sodium benzene sulfinate (61185). Paste A: hydrophobic aromatic and aliphatic dimethacrylate, hydrophilic aliphatic dimethacrylate, sodium aromatic sulfinate (TPBSS), *N*,*N*-diethanol-*p*-toluidine, surface-treated (functionalized) sodium fluoride < 10%, silanated barium glass (61185). Paste B: MDP, hydrophobic aromatic and aliphatic dimethacrylate, hydrophilic aliphatic dimethacrylate, silanated silica, photoinitiator, dibenzoylperoxide (61185)

Abbreviations: MDP, 10-methacryloyloxydecyl dihydrogen phosphate; Bis-GMA, bisphenol-A glycol dimethacrylate; HEMA, 2-hydroxy ethyl methacrylate; TEGDMA, triethylene glycol dimethacrylate; GPDM, glycerol phosphate dimethacrylate; Bis-EMA, ethoxylated bisphenol A glycol dimethacrylate; UDMA, urethane dimethacrylate.

(size 2) following the same protocol as in the VF group.

ED/PF Group—Specimens (n=7) were filled and cured following the previously mentioned protocol in VF and TS/MF groups but using dual-cure self-etch primer adhesive/cement ED primer II/Panvia F2.0 (Kuraray Medical), which was applied according to the manufacturer's instructions. All specimens were stored in distilled water at 37°C for one week before bond strength testing. From each specimen, six horizontal slices of 0.9 ± 0.1 mm thickness each were cut from coronal, middle, and apical thirds of each root (two slices from each third) using a low-speed saw (IsoMet) under water coolant. Each slice was coded, and the apical and coronal diameters of the post were measured using a stereomicroscope (SZ-PT, Olympus, Tokyo, Japan). The exact thickness of each slice was measured using a digital caliper with 0.01-mm accuracy.

Nanoleakage Analysis

Slices were immersed in 50% ammoniacal silver nitrate solution, which was prepared according to the protocol described by Tay and others.[25] The slices were left in the silver nitrate solution in darkness for 24 hours, rinsed thoroughly in distilled water, and immersed in photo-developing solution for eight hours under fluorescent light to reduce silver ions into metallic silver grains within voids along the bonded interface. Slices were then polished using SiC paper of increasing grit size (1200, 2500, and 4000) and rinsed with water for 30 seconds. Slices were then mounted on aluminum stubs. The composite-dentin and composite-post interfaces were analyzed for nanoleakage[26] using field emission scanning electron microscopy (FEG-SEM, Quanta 250, FEI, Eindhoven, The Netherlands) operated in the backscattered-electron/low-vacuum mode. Micrographs were captured at two magnifications (500× and 2500×).

Push-Out Bond Strength Testing

Each root slice was fixed to a specially constructed loading fixture and then subjected to a compressive load via a universal testing machine (Lloyd LRXplus, Lloyd Instruments Ltd, Fareham, United Kingdom) at a crosshead speed of 1 mm/min using three plungers of different sizes (1.3, 1, and 0.75 mm) for coronal, middle, and apical slices, respectively. The plunger tip was positioned so that it contacted only the bonded post. The push-out force was applied in an apico-coronal direction until bond failure oc-

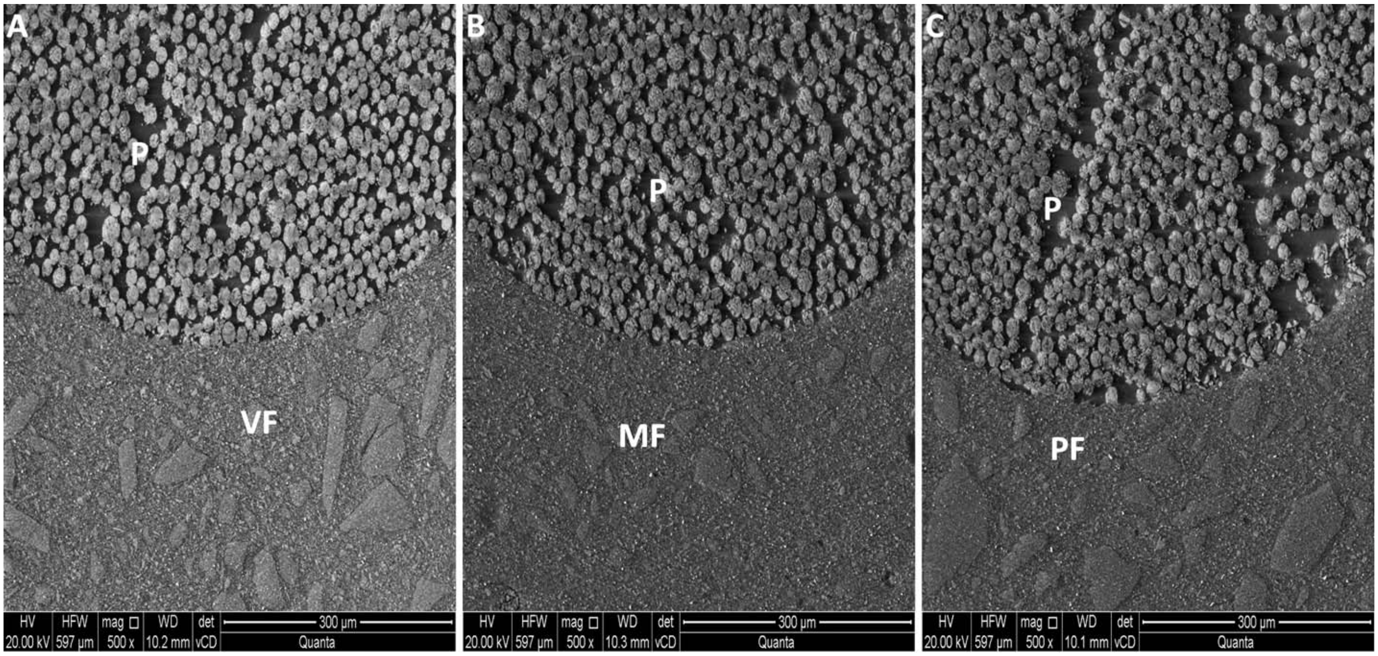

Figure 1. *Representative scanning electron micrographs for the post (P) and resin materials interface: (A) VF, Vertise Flow; (B) MF, Majesty Flow; (C) PF, Panavia F2.0.*

curred, which was manifested by extrusion of the post and a sudden drop along the load/time curve recorded by the testing machine. The maximum failure load was recorded in newtons and was used to calculate the micro push-out bond strength in megapascals (MPa) according to the following formula: Push-out bond strength (MPa) = Maximum load (N)/Post area (mm^2). The post surface area (A) for each section was calculated as $\pi(r1 + r2)\,[(r1 - r2)^2 + h^2]^{0.5}$, where π is the constant 3.14, r1 is the coronal radius, r2 is the apical radius of the post, and h is the thickness of the slice in mm.[27]

Two-way analysis of variance (ANOVA) with repeated measures was used to compare the effect of the adhesive system, canal region, and their interaction. This was followed by the Tukey *post hoc* test for pairwise comparison. The significance level was set at $p \leq 0.05$. Data were analyzed using the SPSS program for windows (Statistical Package for Social Sciences, release 15 for MS Windows, 2006, SPSS Inc, Chicago, IL, USA).

Failure Mode Analysis

Failed parts of the tested slices were mounted on an aluminum stub. Following sputter coating with gold, the slices were analyzed with a scanning electron microscope (SEM, XL30, Philips, Eindhoven, The Netherlands). Images were obtained with backscattered mode. Failure modes were evaluated at 50× and classified as follows: 1) adhesive failure at dentin interface, 2) adhesive failure at the post interface, 3) cohesive failure within the adhesive material, 4) cohesive failure within the post, 5) cohesive failure within the dentin, and 6) mixed failure (adhesive at the dentin interface and cohesive in adhesive layer and/or in resin composite).

RESULTS

Nanoleakage

Representative images of the tested groups can be seen in Figures 1 through 4. Adaptation between the tested adhesives to the posts was confirmed. No silver nitrate deposits were seen for all groups at the resin composite–post interface after storage for one week (Figure 1). However, slight silver nitrate deposits were seen at the composite-dentin interfaces in all groups (Figures 2 through 4). An adhesive layer was detected in the TS/MF and ED/PF groups, where no silver uptake was detected at the interfaces between these adhesive layers and resin composites (Figures 3 and 4).

Push-Out Bond Strength

Two-way ANOVA with repeated measures revealed that there was a statistically significant effect for adhesive systems ($p<0.001$) but not for root region ($p<0.64$) or for their interaction ($p=0.99$). Means and standard deviations of the µPOBS values of all

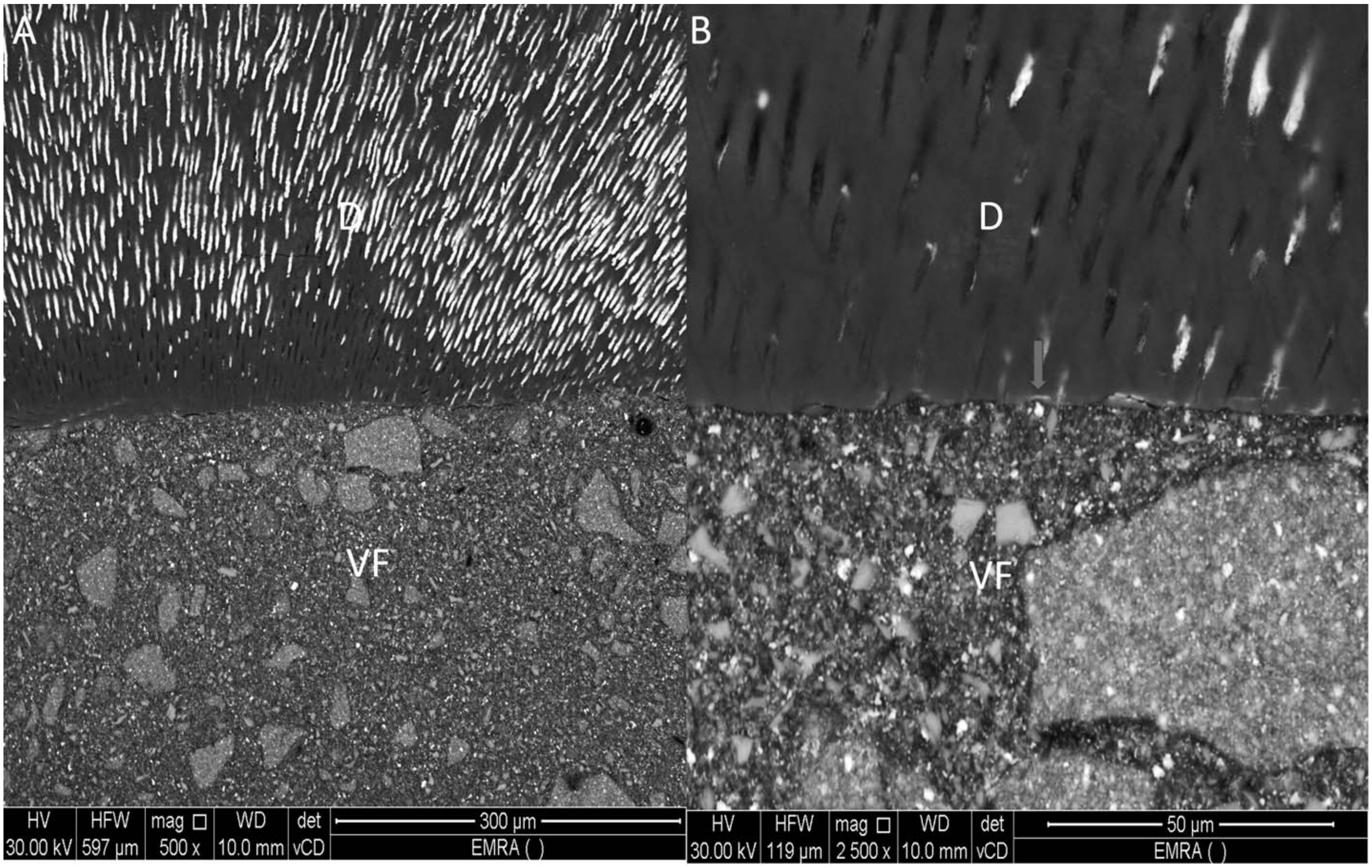

Figure 2. *Representative scanning electron micrographs demonstrating the Vertise Flow (VF) and dentin interface with few silver nitrate uptake (solid arrows). No hybrid layer, adhesive layer, and resin tags were recorded.*

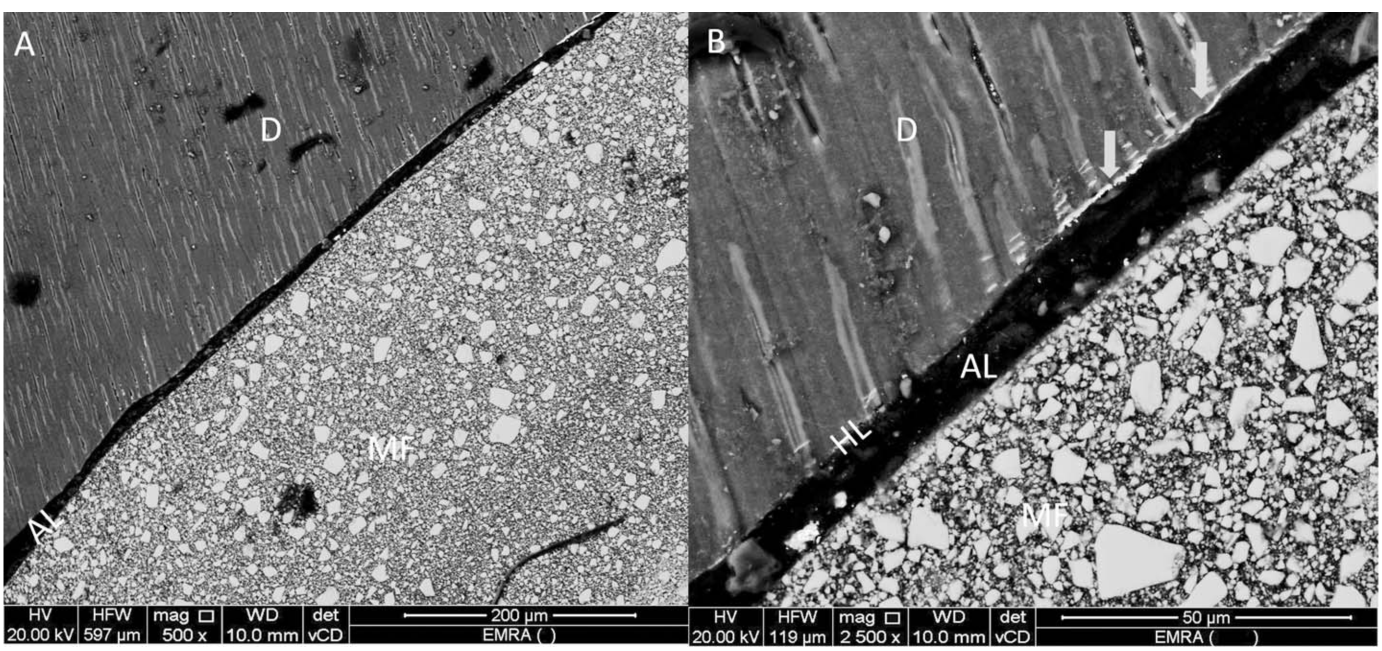

Figure 3. *Representative scanning electron micrographs demonstrating the Clearfil Tri S Bond (TS)/Majesty Flow (MF) and dentin interface with few silver nitrate uptake (solid arrows). Hybrid layer (HL) as well as adhesive layer (AL) were detected, while no resin tags were recorded.*

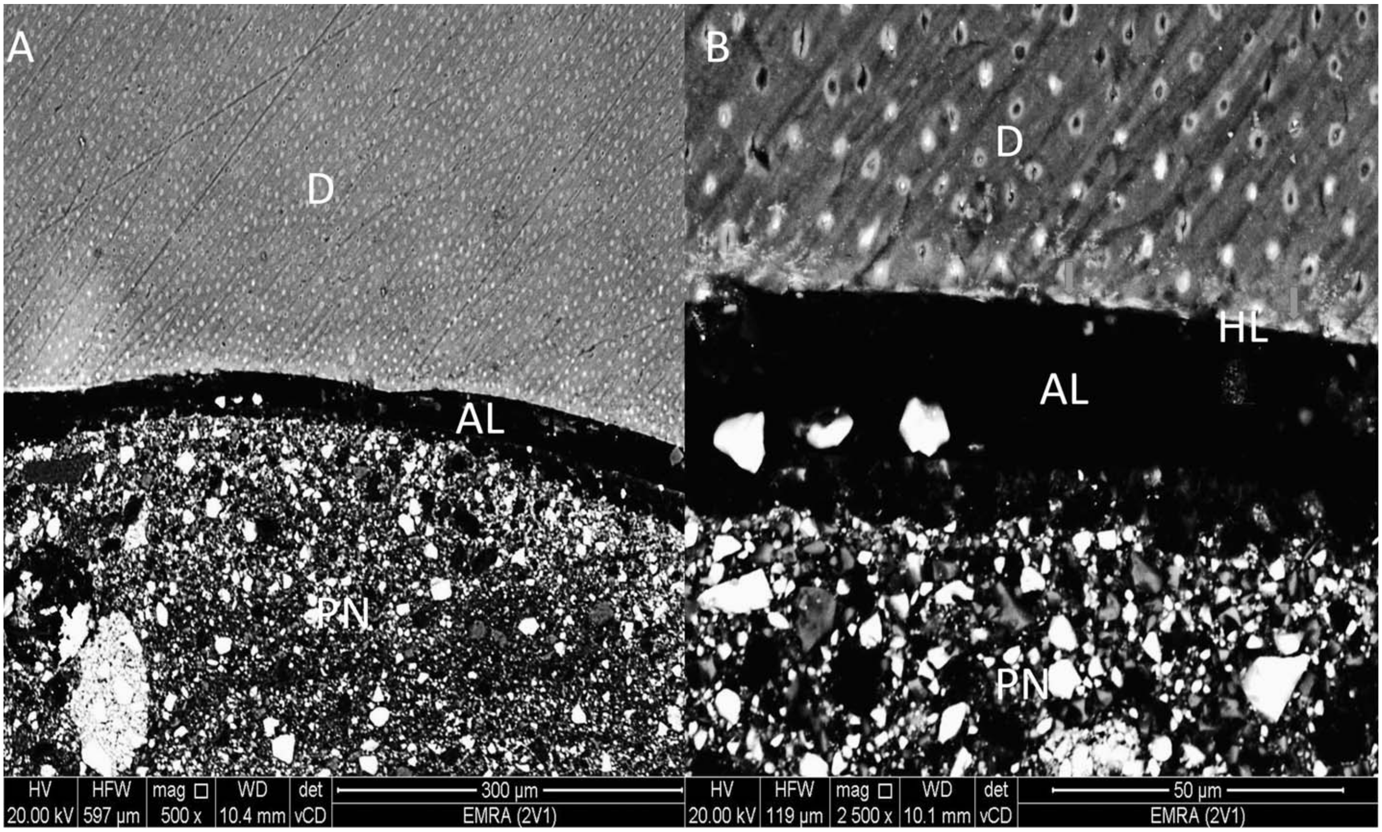

Figure 4. *Representative scanning electron micrographs demonstrating the ED primer II/Panavia F2.0 (PF) and dentin interface with few silver nitrate uptake (solid arrows). Hybrid layer (HL) as well as adhesive layer (AL) were detected, while no resin tags were recorded.*

tested groups are presented in Table 2. There was a significant difference among the adhesive systems for each root region (Table 2). As shown in Table 2, Tukey *post hoc* test revealed that the VF group was significantly higher than the TS/MF and ED/PF groups for all root regions.

Failure Mode Analysis

Failure mode analysis is shown in Figure 5. Exclusive cohesive fracture in the post or in the adhesive material was not seen. Overall, the majority of failures were mainly adhesive at the dentin side rather than mixed failure. Representative SEM

Table 2: *Micro Push-Out Bond Strength (μPOBS) Values (Mean [SD]) in Mpa of Tested Groups*[a]

Root Region	Micro Push-Out Bond Strength Values (Mean [SD]) in (MPa)			
	VF group	TS/MF group	ED/PF group	*p*-Value
Coronal	19.1(5.3) aA	14.4(3.3) bA	13.2(4.2) bA	0.01
Middle	18.6(5.8) aA	13.1(4.3) bA	11.3(2.9) bA	0.00
Apical	18.0(5.5) aA	14.1(4.8) abA	12.8(3.1) bA	0.04
p-Value	0.90	0.78	0.47	

Abbreviations: VF, Vertise Flow; TS, Clearfil Tri S Bond; MF, Majesty Flow; ED, ED primer II; PF, Panavia F 2.0.
[a] *Within rows, means with same small letters denote no statistical significant difference among restorative groups ($p > 0.05$; Tukey test). Within columns, means with same capital letters indicate no statistical significant difference among root regions ($p > 0.05$; Tukey test).*

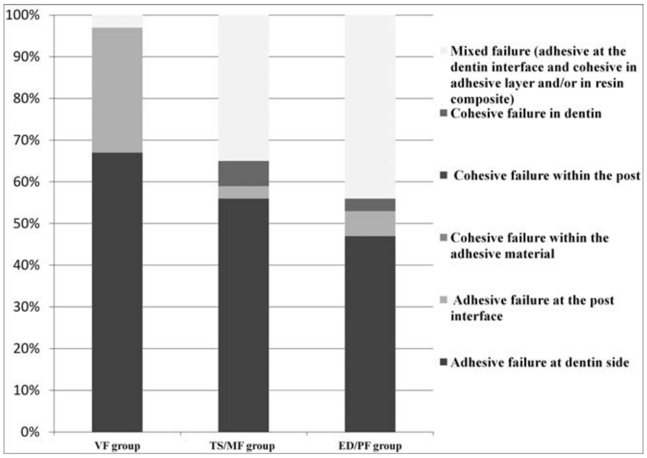

Figure 5. *Modes of failure of tested groups. VF, Vertise Flow; TS, Clearfil Tri S Bond; MF, Majesty Flow; ED, ED primer II; PF, Panavia F2.0.*

images for the detected modes of failure for each group are presented in Figure 6.

DISCUSSION

Achieving good bonding and sealing at the dentin-adhesive system interface are crucial criteria for a restoration to be considered successful, especially when used with weakened tooth structure. In the present study, nanoleakage was analyzed using FE-SEM, which was reported to reveal less accurate observation of nanoleakage within the hybrid layer than did the transmission electron microscope (TEM).[28] Yet FE-SEM enables the entire root slice to be observed without further preparation, reducing the risk of missing the presence of silver particles in areas not sectioned by the ultramicrotome used for TEM specimen preparation.[29] In addition, when FEG-SEM is used for analysis, low vacuum mode can be used. The slices require neither desiccation nor coating with gold-palladium. Thus, their original characteristics can be preserved for further testing. FEG-SEM micrographic pictures showed slight nanoleakage at the dentin interface with all tested adhesives. The slight nanoleakage recorded for the VF group could be attributed to the claimed chemical adhesion to hydroxyapatite of root dentin. The bonding mechanism of the VF is based primarily on the chemical bond between the phosphate functional group of GPDM monomer and calcium ions of the tooth. VF contains fluoride in the fillers. It has been speculated that minor nanoleakage could be related to the water repulsion effect of fluoride, which may help to reduce residual water in the bonding interface and improve its resistance to hydrolytic degradation.[30] There are no data in the available literature concerning the nanoleakage behavior of VF. ED primer II and Clearfil Tri-S Bond, as previously mentioned, contain MDP, which tends to react with hydroxyapatite to form calcium salt.[31] The MDP-calcium salt formed has low water solubility, rendering the interfacial bond hydrolytically stable.[32] The present study results support the suggestion that the use of MLT may decrease the volumetric shrinkage, leading to better adaptation at the interface between dentin and the tested adhesive systems. This is similar to what happens with coronal restorations when the incremental layering technique is applied.[8] However, it should be clearly stated that whether this favorable result would last over time requires further research. Bitter and others[29] recorded distinctive silver uptake with ED primer II/Panavia F2.0 after thermocycling.

In the current study, bond strength was measured using the μPOBS test. This testing method was preferred to other methods, such as pullout testing or microtensile bond strength, for several reasons. One reason is the ease in slice preparation and testing. Also, this testing method allows fabrication of several slices out of one root as well as testing for regional differences among root sections.[24,33] In contrast to microtensile bond strength testing, the push-out design showed no premature failures and an acceptable variability of the data distribution.[34] It was suggested that the push-out bond strength method results in shear stress at the interface between post and cement, causing failures to occur parallel to the post-cement-dentin interface, which is comparable to clinical conditions.[35] However, another study suggested that forces during testing cannot be directly compared with functional forces that the post needs to withstand during clinical service. Also, the effect of friction seems to influence bond strength results.[35,36] It is also possible that the sectioning process can induce artifacts that can result in a relatively high coefficient of variation.[27] In the present study, using the very thin slices (<1 mm thickness), the funnel-shaped preparation,[37] and the placement of slices in an apico-coronal direction during testing might have played a role in minimizing the frictional forces. The cautious sectioning using the slow-speed IsoMet saw prevented sectioning artifacts as confirmed during the inspection of the slices for nanoleakage analysis. A control group in which the tested adhesive materials were applied without MLT (ie, applied in bulk) was not included in the present study. The pilot study showed that this approach revealed a marked gap between the dentin and the adhesive material due to the large

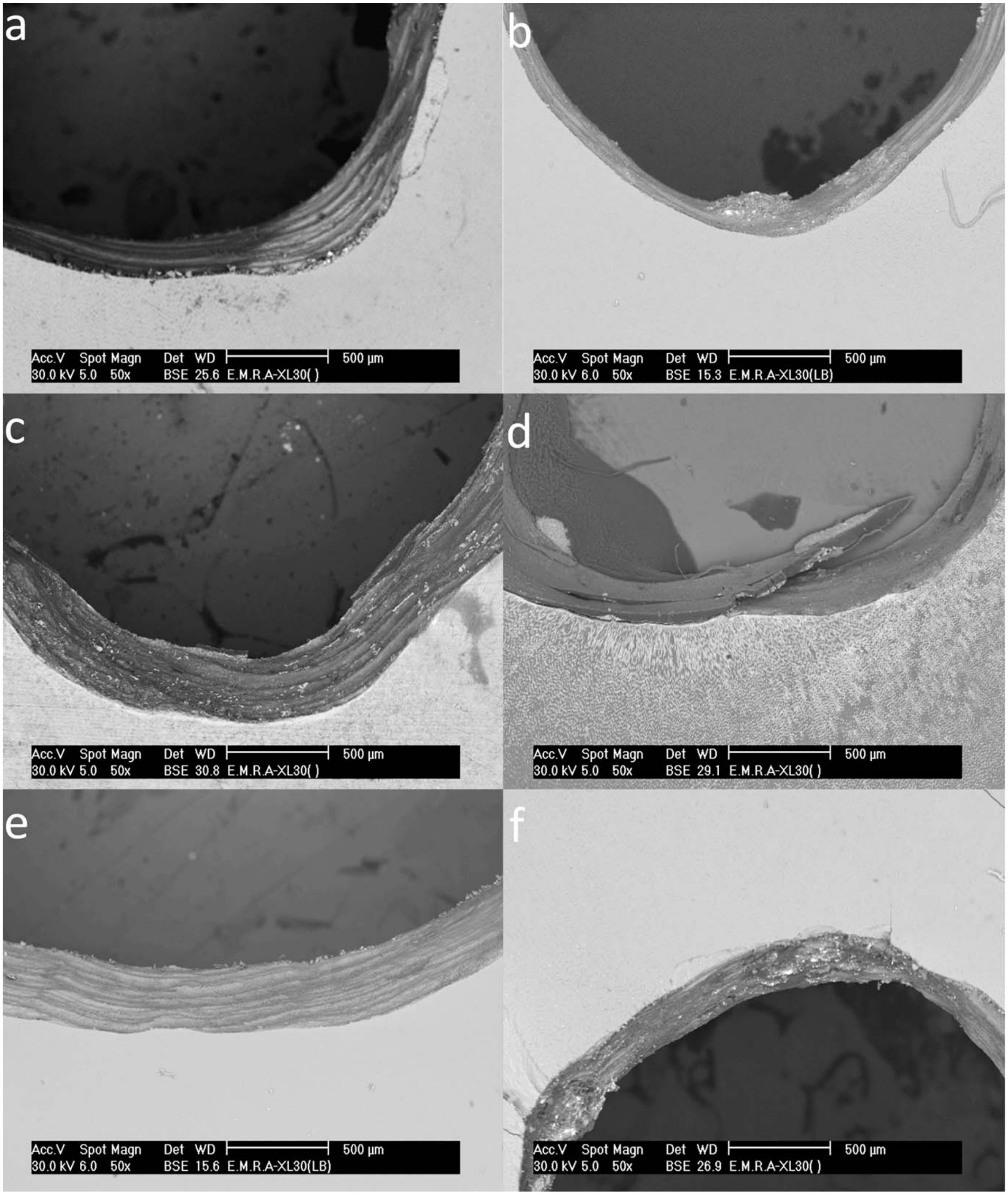

Figure 6. *Representative scanning electron micrographs (SEM) for the most frequently detected mode of failures. a, c, and e show adhesive failure at the dentin interface, while b, d, and f show mixed mode of failure (adhesive at the dentin interface and cohesive in adhesive layer and/or in resin composite) for the VF group, TS/MF group, and ED/PF group, respectively. VF, Vertise Flow; TS, Clearfil Tri S Bond; MF, Majesty Flow; ED, ED primer II; PF, Panavia F2.0.*

volume of the material required to be cured at once. Previous work proved that bulk application of direct resin results in a pulling away of resin from dentin walls, dramatically threatening the tooth-resin bond strength.[37]

In the present study, VF, the self-adhering system, had statistically significant higher bond strength than self-etch systems (Clearfil Tri-S Bond/Majesty Flow as well as ED primer II/Panavia F2.0). This finding suggests the rejection of the second null hypothesis. Although previous studies did not test the same material, they reported statistically higher bonding performance of self-adhering than self-etch systems, which to a certain extent supports our findings.[27,34,38,39] On the other hand, it should be mentioned that other studies contradicted this claim.[33,40] Although the materials used in this study are common in their approach (ie, self-adhesive systems), other factors, such as application technique, chemical composition, and polymerization mode, could have affected their bonding. Panavia F was used after the application of ED Primer II, a two-bottle (Liquid A and Liquid B primers) self-etch adhesive system, while Majesty Flow was applied after Clearfil Tri-S Bond, a single-step self-etch adhesive system. VF is a self-adhering flowable composite. Panavia F2.0 showed the least bond strength. This might be due to its unfavorable cohesive strength,[27] which was manifested in the present study with a higher percentage of mixed mode of failure. For the polymerization mode, most studies have recommended the use of self-cured or dual-cured adhesives to guarantee adequate polymerization, especially in the apical part of the post space.[11,12] Yet in our study, the dual-cured Panavia F2.0 did not perform better than the light-cured tested materials. Other investigators also found no difference[41] or even better performance[42] of light-cured to dual-cured adhesive systems. Interestingly, the current study result corroborated these studies despite the expected larger material volume that had to be cured as the canals were enlarged, simulating weakened roots. However, the use of MLT allowed the control of volume of material to be cured.

Bonding to root dentin is still a challenge because of root dentin regional differences in bond strength. Many studies have shown that the cervical bond strength was higher than the middle and apical ones.[24,39,40] Regional differences in bond strength were attributed to the difficulty in visualization and access to the apical part.[43] Differences in polymerization degree throughout the root length as well as the C-factor are also important factors.[44] Additionally, variation in quantity, volume, and orientation of the tubules toward the apical portion of the root canal might play a role, making it difficult for the adhesive system to penetrate and form resin tags.[42] All materials used in this study showed no difference in bond strength at different root regions, thus corroborating the third hypothesis. The indifference in regional bond strength reported for VF echoed that of Giachetti and others.[41] Also, the results of Panavia F2.0 agreed with other studies.[33,34,42,43] No data could be retrieved regarding the regional bond strength of Clearfil Tri-S Bond to root dentin.

The present study results might be attributed to some factors: The funnel-shaped preparation might have allowed proper material application at the apical part even with VF, which required agitation according to the manufacturer's instructions. The use of the high-intensity LED light-curing unit, together with the new suggested modified-layering technique used in the present study, might have allowed proper polymerization even at the apical part of the post space. Other researchers who found no regional differences in bond strength values expected that the light passing through a light-transmitting post might be able to activate the thin resin layer surrounding the post surface, enabling the resin to cure promptly along the post.[44] The successive usage of light-transmitting post in the modified-layering technique might have also decreased the C-factor. The lack of adhesion between the light-transmitting posts and tested materials was confirmed by the ease of post removal after curing. Another reason for the insignificant difference among root regions might be the self-adhesive approach of all tested adhesive systems. The effect on bond strength due to regional difference seems to be more pronounced in the etch-and-rinse approach but has less effect on self-adhesive systems.[42] Self-adhesive systems bond to the superficial layer of dentin and do not completely remove the smear plugs.[42,45] Thus, their bonding efficacy may be more dependent on the formation of the hybrid layer than on resin tags, where the surface area of intertubular dentin plays a greater role rather than the number of dentinal tubules available for penetration. This was confirmed by FEG-SEM, where no resin tags were seen in the present study.

Analysis of the failure modes in the present study revealed that most failures occurred between dentin and tested adhesive systems, which is in accordance with the results of published investigations.[27,33,34,43] In the present study, no silane pretreatment was performed on the post surface, yet we had fewer adhesive failures at the post interface. For Panavia F2.0, this might be attributed to bonding between MDP and the epoxy matrix of DT Light post.[46] However, Clearfil Majesty Flow and VF have no MDP in their chemical composition. The current study, and other *in vitro* studies,[35,40] support the general clinical finding that fewer failures were noted at the post interface, indicating that no post pretreatment is needed. On the other hand, since the weak point was at the dentin side, dislodgement would be the main problem in such instances. Meanwhile, direct application of the results of the present study to clinical situations should be done with caution, as the longer storage time and/or thermal cycling might give different results.

CONCLUSIONS

All of the tested self-adhesive systems that cured using MLT had slight nanoleakage and were not sensitive to root regional differences. Self-adhering systems had higher bond strength than the other self-etch adhesives.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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