Influence of dentin bonding agents and polymerization modes on the bond strength between translucent fiber posts and three dentin regions within a post space

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Statement of problem. Debonding is the most frequent failure encountered with translucent fiber posts and usually occurs along the post space dentin-adhesive interface.

Purpose. The purpose of this study was to evaluate the effect of different dentin bonding agents and polymerization modes on the bond strength between translucent fiber posts and root dentin in different regions of the post space.

Material and methods. Forty maxillary canines with similar root lengths were selected, sectioned at the cemento-enamel junction, and the roots were endodontically treated. Following post space preparation, the roots were divided into 4 groups of 10 specimens each, and the post spaces were treated with 1 of 4 different dentin bonding agents: light-polymerized, single-bottle bonding agent Excite (Group EX); dual-polymerized, single-bottle bonding agent Excite DSC (Group EX-DSC); self-etching primer Clearfil Liner Bond 2V with a light-polymerized bonding agent, Bond A (Group CL-LC); or self-etching primer Clearfil Liner Bond 2V with a dual-polymerized bonding agent, Bond A+B (Group CL-DC). Translucent fiber posts (D.T. LightPost, 2.2 mm in diameter, were luted (Panavia F) in each specimen after respective dentin bonding procedures. The roots were cut into 3-mm thick sections, perpendicular to the long-axis in cervical, middle, and apical post space dentin. Push-out tests were performed with a universal testing machine at a crosshead speed of 0.5 mm/min, and bond strength values (MPa) were calculated by dividing the force at which bond failure occurred by the bonded area of the post. The data were analyzed with 1- and 2-way analysis of variance and Tukey multiple comparison tests (α=0.05). Dentin adhesive bonding mechanisms in different regions of the post spaces were evaluated with a scanning electron microscope.

Results. The highest mean bond strength values were obtained for Group CL-LC (18.3 ± 4.1 MPa). The dual-polymerized bonding agent resulted in significantly lower bond strength (P<.001) in combination with self-etching primer (Group CL-DC) (13.2 ± 2.5 MPa). The light-polymerized and dual-polymerized single-bottle bonding agents provided similar bond strengths (12.7 ± 5.0 for EX; 13.5 ± 5.3 for EX-DSC). The regional bond strength values of single-bottle bonding agents were reduced significantly in apical post space dentin (P<.001). Self-etching primers did not demonstrate regional differences in post space dentin bonding and dense resin tags were apparent.

Conclusion. Data suggests that the self-etching primer system used in this study was unaffected by the morphological variations in the post space dentin compared to the single-bottle bonding agents. Dual polymerization did not improve the bond strength values of the bonding agents tested. (J Prostheth Dent 2006;95:368-78.)

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CLINICAL IMPLICATIONS

Within the limitations of this in vitro study, a self-etching primer and light-polymerized bonding agent combination were recommended for luting of translucent fiber posts with a dual-polymerized resin luting agent.

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In recent years, foundation materials chosen for restoring endodontically treated teeth have changed from exclusively rigid materials (metal and zirconium posts) to materials having mechanical characteristics more closely resembling dentin (fiber posts and composite resin). Fiber posts consist of fibers (carbon, quartz, silica, zircon, or glass) in a resin matrix with a silane coupling agent binding the fibers and matrix together. These posts are chemically compatible with the bisphenol-glycidyl methacrylate (Bis-GMA)-based resin luting agents commonly used in bonding procedures, and they can be cemented with an adhesive technique.

A concern for improved esthetics promoted the introduction of translucent fiber posts preferred for supporting all-ceramic coronal restorations, especially with anterior teeth. In addition to the favorable physical properties of the fiber posts, light can be transmitted...
through the posts, permitting light polymerization of adhesive materials in post spaces. Recently, prospective clinical studies have demonstrated the efficacy of translucent fiber posts and identified debonding along the dentin–resin luting agent interface as the most frequently encountered mode of failure.

The retention of fiber posts in roots depends on the bond strength between the post material and a resin luting agent, as well as the bond strength between the resin luting agent and post space dentin. Previously conducted scanning electron microscope (SEM) studies demonstrated an absence of voids and bubbles at the interface between resin luting agent and translucent fiber posts, indicating a good bond between the resin matrix of the posts and resin luting agent. Also, different types of surface treatments have been investigated in an attempt to improve the bonding of resin luting agents to fiber posts. These treatments include airborne-particle abrasion, silane treatment, and airborne-particle abrasion with silica-coated alumina particles. However, Sahafi et al. indicated that limited adhesion between a resin luting agent and post space dentin was responsible for the ineffectiveness of several surface treatments on post retention. Similarly, Bocchim Pest et al. compared bond strengths between post space dentin and a resin luting agent, and the resin luting agent and fiber posts, and reported significantly lower strength values for bonds between post space dentin and resin luting agent.

The morphological differences between coronal dentin and post space dentin should be considered, and the appropriate bonding agent for adhesive cementation of endodontic posts should be selected according to those variations. Another important factor is the morphological differences between different regions of the post space dentin. Originally, fiber posts were recommended for use with 3-step dentin bonding systems that require separate etching, priming, and bonding procedures. In an effort to simplify bonding procedures, single-bottle bonding agents that combine primer and bonding resin components in 1 solution have been introduced, and their clinical indications have rapidly increased for bonding of fiber posts and indirect esthetic restorations. It is well known that the wet bonding technique is essential for the single-bottle primer/adhesive systems to achieve an optimal hybrid layer and, therefore, improve the dentin bond strength. However, the level of moisture left on the dentin surface is difficult to determine, and this factor significantly influences the bond strength. It is more likely that bonding problems will occur within the confines of a post space because the space cannot be adequately visualized. Furthermore, it is difficult to control moisture in a post space since the walls of the narrow space hold water by surface tension, making it difficult to displace water with a bonding agent.

The use of self-etching primers in combination with resin luting agents has also been proposed for cementation of endodontic posts to eliminate the problems associated with the moist application technique. Self-etching primers eliminate the conditioning, rinsing, and drying steps and may cause less damage to dentinal surfaces compared to acidic conditioners. They have demonstrated similar or higher bond strengths in different regions of coronal dentin compared to other dentin bonding systems requiring a separate etching step. However, their bonding efficacy in different regions of the post space dentin has not been extensively investigated.

It is critical that all bonding components at the adhesive interface undergo maximum polymerization to ensure optimal bond strength. Both resin luting agents and bonding agents are available in light-polymerized, autopolymerized, or dual-polymerized adhesive formulations. According to Roberts et al., the use of translucent fiber posts resulted in a greater hardness value for a light-polymerized resin composite material due to the light-transmitting properties of the post. For this reason, dual-polymerized resin luting agents that also have a light-polymerizing component were preferred over the autopolymerizing products for luting translucent fiber posts. Nonetheless, light-polymerized dentin bonding agents were commonly used in combination with the resin luting agents. However, due to difficulties in transmitting light to the apical region of a post space, the use of dual-polymerizing dentin bonding agents may provide a more reliable bond to post space dentin.

Post retention in different regions of a post space has been measured with microtensile and push-out tests. It has been suggested that, due to the small size of specimens, the microtensile test permits a more uniform stress distribution along the bonded interface. However, in a recent study, Goracci et al. revealed that the push-out test is a more reliable method for determining bond strengths between fiber posts and post space dentin because of the high number of premature failures occurring during specimen preparation and a large data distribution spread associated with microtensile testing.

Based on these considerations, the purpose of this study was to evaluate the effect of the different dentin bonding agents and their polymerization modes on bond strengths between translucent fiber posts and post space dentin in different regions of the post space using a push-out test. The hypotheses to be tested were: (1) self-etching primers provide greater bond strength compared to single-bottle bonding agents; (2) dual-polymerized bonding agents result in greater bond strength compared to light-polymerized bonding agents; and (3) there are measurable bond strength differences in different post space regions.
Table I. Materials selected for this study

<table>
<thead>
<tr>
<th>Materials</th>
<th>Manufacturer</th>
<th>Type</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT Light-Post</td>
<td>Recherches Techniques Dentaires, St. Egreve, France</td>
<td>Translucent quartz fiber post</td>
<td>Quartz fibers: 60% volume</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Epoxy resin: 40% volume</td>
</tr>
<tr>
<td>Excite</td>
<td>Ivoclar Vivadent, Schaan, Liechtenstein</td>
<td>Light-polymerizing single-bottle bonding agent</td>
<td>Phosphoric acid acrylate, dimethacrylates, HEMA, Bis-GMA, highly dispersed silicon dioxide, ethanol, catalysts, stabilizers</td>
</tr>
<tr>
<td>Excite DSC</td>
<td>Ivoclar Vivadent</td>
<td>Dual-polymerizing single-bottle bonding agent</td>
<td>Phosphoric acid acrylate, dimethacrylates, HEMA, highly dispersed silicon dioxide, ethanol, catalysts, stabilizers, Microbrush: coated with initiators Primer A and B: MDP, HEMA, hydrophilic methacrylate, dl-camphorquinone, N,N-diethanol-p-toluidine, H2O Bonding A: MDP, Bis-GMA, HEMA, dl-camphorquinone, N,N-diethanol-p-toluidine, silanated colloidal silica</td>
</tr>
<tr>
<td>Clearfil Liner Bond 2V</td>
<td>Kuraray Co Ltd, Osaka, Japan</td>
<td>Self-etching primer</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>A: light-polymerizing</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>A+B: dual-polymerizing</td>
<td></td>
</tr>
<tr>
<td>Panavia F</td>
<td>Kuraray Co Ltd</td>
<td>Dual-polymerizing resin luting agent</td>
<td>Paste A: Silanated silica, microfiller, MDP, dimethacrylates, photo/chemical initiator Paste B: Silanated barium glass, surface-treated NaF, dimethacrylates, chemical initiator</td>
</tr>
</tbody>
</table>

HEMA, 2-Hydroxyethyl methacrylate; Bis-GMA, bisphenol-glycidyl methacrylate; MDP, 10-methacyrloyloxydecyl dihydrogen phosphate; NaF, sodium fluoride.

MATERIAL AND METHODS

Two single-bottle dentin bonding agents with similar chemical composition, one in light-polymerized and the other in dual-polymerized adhesive formulations, and a self-etching primer that can be used in combination with a light- or dual-polymerized dentin bonding agent were selected in the present study (Table I). The diameter of the fiber posts tested was 2.2 mm at the coronal end and 1.2 mm at the apical end. The posts had a tapered design with smooth surfaces and were 20 mm in length.

Forty maxillary canines extracted for periodontal reasons, with similar root length and free of cracks, caries, and fractures, were selected and stored in 0.9% saline solution (Baxter Healthcare Corporation, Deerfield, Ill) no longer than 1 week following extraction. Teeth with excessive root curvature were not selected. All teeth were sectioned perpendicular to their long axes at the cemento-enamel junction with a low-speed saw (Isomet; Buehler Ltd, Lake Bluff, Ill) under water cooling. The root canals were mechanically enlarged using endodontic files (Hero 642; Micro-Mega SA, Geneva, Switzerland) operated at 400 rpm under a constant irrigation with 3% NaOCl. The final preparations had a 6-degree taper and a 0.3-mm diameter at the apex. The enlarged canals were rinsed with distilled water, dried with paper points, and obturated with gutta-percha cones and lateral condensation (Gutta Percha Points; United Dental, West Palm Beach, Fla) using a eugenol-free sealer (AH 26; Dentsply DeTrey, Konstanz, Germany).

The post spaces were prepared 24 hours after completing endodontic procedures. Gutta-percha was removed with a warm endodontic plugger (Sybron Dental Specialties, Romulus, Mich), and subsequently, the post preparations were made with a drill (#3 DT Light-Post drill; Recherches Techniques Dentaires, St. Egreve, France) to a depth of 10 mm measured from the sectioned root surface. The drills were designed to allow a minimum of 30 μm space around the posts for the luting agent. This also ensured that posts would reach the bottom of the post space during cementation, according to the manufacturer's recommendations. Following the post space preparations, the spaces were rinsed for 1 minute with 3% NaOCl. A final irrigation was accomplished with distilled water, and then the post spaces were dried with paper points (Roeco, Langenau, Germany). The roots were divided into 4 groups of 10 specimens each for bonding procedures (Table II).
### Table II. Test groups and bonding procedures

<table>
<thead>
<tr>
<th>Group</th>
<th>Dentin conditioner</th>
<th>Procedure</th>
<th>Bonding agent</th>
<th>Procedure</th>
<th>Resin luting agent</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>EX</td>
<td>37% H₃PO₄</td>
<td>Apply 15 s. Rinse 20 s. Dry with paper points. Leave dentin moist.</td>
<td>Excite</td>
<td>Apply 10 s. Remove excess with paper points. Air dry 5 s. Light polymerize 20 s.</td>
<td>Panavia F</td>
<td>Mix base and catalyst 20 s. Apply to root canal with lentulo drill. Remove resin excess with small brush. Apply 5 kg axial load for 60 s. Light polymerize 20 s through translucent fiber post.</td>
</tr>
<tr>
<td>EX-DSC</td>
<td>37% H₃PO₄</td>
<td>Apply 15 s. Rinse 20 s. Dry with paper points. Leave dentin moist.</td>
<td>Excite DSC</td>
<td>Apply 10 s. Remove excess with paper points. Air dry 5 s. Light polymerize 20 s.</td>
<td>Panavia F</td>
<td></td>
</tr>
<tr>
<td>CL-LC</td>
<td>Primer A+B</td>
<td>Mix primer A and B. Apply 30 s. Remove excess with paper points. Air dry 5 s.</td>
<td>Bond A</td>
<td>Apply Bond A 30 s. Remove excess with paper points. Air dry 5 s. Light polymerize 20 s.</td>
<td>Panavia F</td>
<td></td>
</tr>
<tr>
<td>CL-DC</td>
<td>Primer A+B</td>
<td>Mix primer A and B. Apply 30 s. Remove excess with paper points. Air dry 5 s.</td>
<td>Bond A+B</td>
<td>Mix Bond A and B. Apply 30 s. Remove excess with paper points. Air dry 5 s. Light polymerize 20 s.</td>
<td>Panavia F</td>
<td></td>
</tr>
</tbody>
</table>

In group EX, the root specimens were treated with a light-polymerized single-bottle dentin bonding agent (Excite). The post space walls were etched with 37% phosphoric acid gel (Total Etch; Ivoclar Vivadent). The gel was introduced into the spaces with a needle, and after 15 seconds it was rinsed from the post space walls with distilled water using an endodontic syringe (Monosect endodontic syringe; Tyco, Mansfield, Mass). Excess water was removed from the post spaces with a gentle stream of air and paper points. The primer-adhesive was applied to the post space dentin with a microbrush (Microbrush X; Microbrush Corp, Grafton, Wis) for 10 seconds. Excess primer-adhesive solution was absorbed with paper points, gently air dried, and then light polymerized using a halogen light unit with 800-mW/cm² intensity (Optilux 501; Kerr Dental, Orange, Calif) for 20 seconds, with the tip of the light unit directly in contact with the post space opening. Light output was monitored to ensure accurate light intensity before each exposure using the digital radiometer built into the light unit. For EX-DSC specimens the same bonding protocol was used as that described for group EX. A dual-polymerized single-bottle dentin bonding agent (Excite DSC) was applied with a microbrush coated with chemical initiators, which was provided by the manufacturer. For CL-LC specimens, one drop each of Primer A and B was mixed and applied to the post space walls with a microbrush for 30 seconds. Excess primer solution was removed with paper points, and the primer was then gently air dried. Bond A was applied with a microbrush, excess adhesive solution was removed
with paper points, and the bonding agent was light polymerized for 20 seconds. In group CL-DC, the same bonding procedure was used as described for group CL-LC, except that a 1:1 mixture of Bond A and Bond B was used as the dual-polymerizing bonding agent.

Before cementation, each post was marked at a distance of 10 mm from the apical end corresponding to the length of the post space preparation and sectioned horizontally with a water-cooled diamond rotary cutting instrument (R879.014; Diaviss, Geneva, Switzerland). For cementation of fiber posts, equal amounts of a dual-polymerized resin luting agent (Panavia F) paste base and catalyst were mixed and applied to the post space walls with a lentulo spiral instrument (Dentsply Maillefer, Ballaigues, Switzerland). The posts were then seated to full depth in the prepared spaces using finger pressure, and excess luting agent was immediately removed with a small brush. An axial load of 5 kg was applied for 60 seconds to stabilize the fiber posts in the post spaces. After the initial chemical polymerization, the resin luting agent was light polymerized for 20 seconds through the posts, with the tip of the light unit in direct contact with the coronal end of the posts. After the cementation procedures, all root specimens were stored in distilled water for 24 hours before testing.

The specimens were attached to the arm of a low-speed saw (Isomet; Buehler Ltd) and sectioned perpendicular to the long axis under water cooling. From each specimen, 3 post/dentin sections (cervical, middle, and apical) were obtained, each 3 mm thick. Thus, each study group of 10 roots provided a total of 30 test specimens, consisting of 10 specimens from each of the 3 different post space regions. The exact length of fiber post segments in each section was measured using a digital micrometer (Mitutoya, Tokyo, Japan) with 0.01-mm accuracy. Due to the tapered design of the fiber posts, segments in each section had a truncated cone shape. For this reason, post diameters were measured on each surface of the post/dentin sections using the digital caliper, and the total bonding area for each post segment was calculated (Fig. 1).

Push-out tests were performed using a customized stainless steel push-out device, which consisted of a metal block base and, above the base, 2 parallel metal supports (height, 10 mm) separated by a 3.0-mm space. The post-dentin interface and the post surface on the cervical side of the post/dentin specimens were covered with a petroleum jelly (Vaseline; Unilever, Greenwich, Conn). A cyanoacrylate adhesive (Zapit; Dental Ventures of America Inc, Corona, Calif) was applied to dentin on the cervical side to secure specimens to the push-out device supports during testing. Then, each post/dentin section was attached to the device, ensuring that the coronal surface of the post/dentin section faced the device and the post was centered over the space between the supports (Fig. 2). The post segments were loaded with a cylindrical plunger, 1.2 mm in diameter, centered on the post segment and avoiding contact with the surrounding dentin surface. Loads were applied from an apical to cervical direction with respect to individual test specimens with a universal testing machine (HA 100; Dartec, Surrey, UK) at a crosshead speed of 0.5 mm/min. The peak force, at the point of extrusion of the post segment from the test specimen, was taken as the point of bond failure and recorded in newtons (N). Push-out bond strength values in MPa were then calculated by dividing this force by the bonded area of the post segment.

Data analysis was performed in several steps. Initially, a 2-way analysis of variance (ANOVA) was performed to
Table III. Results of 2-way ANOVA

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>df</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected model</td>
<td>11</td>
<td>1709.7</td>
<td>155.4</td>
<td>14.9</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Intercept</td>
<td>1</td>
<td>24912.0</td>
<td>24912.0</td>
<td>2381.3</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Bonding agent</td>
<td>3</td>
<td>602.5</td>
<td>200.8</td>
<td>20.2</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Post space region</td>
<td>2</td>
<td>769.8</td>
<td>384.9</td>
<td>36.8</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Bonding agent × Post space region</td>
<td>6</td>
<td>317.3</td>
<td>52.91</td>
<td>5.4</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Error</td>
<td>108</td>
<td>1129.8</td>
<td>10.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>120</td>
<td>2775.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected total</td>
<td>119</td>
<td>2839.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Independent variables: bonding agent, post space region; dependent variable: push-out bond strength.
df: Degrees of freedom.

examine the main effects of the dentin bonding agent, post space region, and the interaction between these 2 factors. Secondly, the bond strength values of the 3 different post/dentin sections were pooled together for each group, and the average dentin bond strengths were calculated for the groups. Mean values were compared with a 1-way ANOVA, followed by a multiple comparisons test performed using a Tukey honestly significant difference (HSD) test. Statistical significance was set at the 5% level.

Resin-dentin interdiffusion zones (hybrid layer) and resin tag formations in cervical, middle, and apical regions were examined with SEM to evaluate the bonding mechanism of the dentin bonding agents to the different post/dentin regions. This was attempted to demonstrate a correlation among hybrid layer thickness, length, and density of the resin tags and push-out bond strength. However, it was not possible to make these observations in specimens used in the push-out test due to the adhesive and cohesive types of failures, which occurred during debonding of the post sections. For this reason, as in a previous study,14 a separate specimen preparation protocol was used for the SEM observations, and 3 specimens from each group were similarly prepared as described for the push-out test specimens.

The root sections were cut parallel to the long axis of the tooth in a mesial-distal direction using the same low-speed saw under water cooling after storage in distilled water for 24 hours. The resulting 6 dentin-adhesive interface specimens for each group were divided into 2 subgroups (n=3) and prepared for SEM by using one of the following techniques: one section of each tooth was gently decalcified with 32% phosphoric acid for 30 seconds, rinsed with distilled water, and subsequently deproteinized by immersion in a 2% NaOCl solution for 120 seconds to evaluate the resin-dentin interdiffusion zone formation; the other section of each tooth was stored in 30% HCl for 24 hours to completely dissolve the dental substrate and to detect resin tag formation. After rinsing with water and air drying, the specimens were mounted on aluminum stubs and sputter coated with gold palladium (Hummer II Sputter Coater; Technics Inc, Alexandria, Va) for 3 minutes at a current of 10 mA. Cervical, middle, and apical post space regions of each specimen were examined with SEM (JSM 6400; JEOL Ltd, Tokyo, Japan) at magnification ×1000.

RESULTS

As seen in Table III, the 2-way ANOVA demonstrated that the bond strength values were significantly affected by the bonding agent (P<.001) and the post space region (P<.001). There was also a significant interaction (P<.001) between the bonding agent and the post space region. The mean bond strength values and SDs for each dentin bonding agent are provided in Table IV. The results of the 1-way ANOVA indicated significant differences between the bonding agents (P<.001). Further analysis with the Tukey HSD test revealed that CL-LC demonstrated significantly higher bond strengths compared to the other dentin bonding agents (P<.001). However, CL-DC demonstrated similar bond strengths to the single-bottle dentin bonding agents EX (P=.994) and EX-DSC (P=.891). When considering the polymerization mode, the light-polymerized bonding agent provided a significantly higher bond strength compared to the dual-polymerized bonding agent for the self-etching primer system (P<.001) (Groups CL-LC and CL-DC, respectively). No significant differences were detected between Groups EX and EX-DSC, the light-polymerized and dual-polymerized single-bottle bonding agents groups (P=.967).

The mean regional bond strength values for cervical, middle, and apical post sections for each group are presented in Table V. One-way ANOVA tests were performed separately for each dentin bonding agent to evaluate the influence of the different post space dentin regions on the bond strength. Results showed that only single-bottle bonding agents were affected by the dentin region (P<.001). Their bond strength values in the apical post space dentin region were significantly lower than cervical and middle post space regions for EX and EX-DSC dentin bonding agents (P<.001), whereas there was no significant difference between cervical
Table V. Regional push-out bond strength values (mean ± SD) in MPa and results of 1-way ANOVA tests performed separately for each dentin bonding agent to evaluate influence of post space dentin regions

<table>
<thead>
<tr>
<th></th>
<th>Cervical</th>
<th>Middle</th>
<th>Apical</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>EX</td>
<td>16.7 ± 3.2 A</td>
<td>14.2 ± 2.9 A</td>
<td>7.1 ± 2.6 B</td>
<td>28.91</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>EX-DSC</td>
<td>17.8 ± 3.3 A</td>
<td>15.1 ± 3.5 A</td>
<td>7.6 ± 2.5 B</td>
<td>28.09</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>CL-LC</td>
<td>19.4 ± 4.9 A</td>
<td>18.3 ± 3.9 A</td>
<td>17.1 ± 3.6 A</td>
<td>0.73</td>
<td>.488</td>
</tr>
<tr>
<td>CL-DC</td>
<td>14.4 ± 2.0 A</td>
<td>13.0 ± 2.4 A</td>
<td>12.2 ± 2.7 A</td>
<td>2.10</td>
<td>.141</td>
</tr>
</tbody>
</table>

Uppercase letters represent comparisons between cervical, middle, and apical post space regions performed separately for each bonding agent. Mean values with different letters are statistically significant at P<.001 level.

Fig. 3. Representative SEM photomicrograph of specimens treated with different dentin bonding agents demonstrating hybrid layer formations (original magnification ×1000). (H) Hybrid layer, (RC) resin cement, (RT) resin tag. **A**, Representative uniform hybrid layer formation with thickness of 4 to 5 μm along entire post space dentin treated with EX. **B**, Representative thin hybrid layer with 1- to 2-μm thickness was formed along entire post space dentin surface treated with CL-LC.

and middle post space regions. Bond strengths for all 3 post space regions were similar for CL-LC (P=.488) and CL-DC (P=.141).

The SEM analyses performed for evaluating the resin-dentin interdiffusion zone revealed a relatively thick hybrid layer (4-5 μm) for EX and EX-DSC, and the hybrid layer was homogeneously distributed along the post space dentin (Fig. 3, A). The CL-LC and CL-DC specimens revealed uniform but thin hybrid layers (1-2 μm) along the entire post space dentin (Fig. 3, B).

The resin tag observations revealed different patterns between the different dentin bonding agents and post space dentin regions. The EX and EX-DSC specimens exhibited long and uniform resin tags in cervical post space dentin (Fig. 4, A), whereas the length and density of the resin tags were reduced in the apical post space dentin (Fig. 4, B). For CL-LC, resin tags in cervical post space dentin were thicker than EX and EX-DSC (Fig. 5, A). A reduction in length was also evident in the apical post space region; however, density and length were much greater compared to single-bottle bonding agents (Fig. 5, B). For CL-DC, resin tags in cervical post space dentin were shorter than those observed in the other dentin bonding agents (Fig. 6, A). The length of resin tags in the apical region did not differ, but a minor reduction in density could be detected. Compared to the EX and EX-DSC groups, long, dense resin tags could be observed (Fig. 6, B).

**DISCUSSION**

According to the results of this study, the strength of the bond to post space dentin was highest with a self-etching primer used in combination with a light-polymerized bonding agent. Therefore, the first hypothesis of this study, that self-etching primers provide greater bond strength compared to single-bottle bonding agents, was accepted. The bonding agents were chosen to represent 2 different product categories that could be used to simplify procedures for bonding fiber posts to post space dentin. Excite is a single-bottle bonding agent intended for use with phosphoric acid. It contains a strong acid that effectively removes the smear layer and exposes the tubule apertures, collagen fibrils, and interfibrillar spaces. However, the etching effect of the Clearfil Liner Bond 2V is related to the acidic monomer, 10-methacyloxydecyl dihydrogen phosphate (MDP), which does not dissolve the smear.
layer and results in a mild demineralization of dental tissues.\textsuperscript{21}

The micromechanical retention to tooth structure occurs when the dentin bonding agent completely infiltrates demineralized dentin surfaces and creates a hybrid or resin-reinforced layer.\textsuperscript{31} A hybrid layer is the result of resin monomer penetration into the exposed collagen network on a conditioned dentin surface.\textsuperscript{21} It is generally accepted that the smear layer that forms on ground dentin surfaces should be removed or altered with an acidic conditioner to obtain good adhesion between the demineralized dentin substrate and an applied bonding system.\textsuperscript{32} The major concern with the self-etching primers is their efficacy in infiltrating thin smear layers such as those produced during post space preparations. However, it has been found that the self-etching primers can penetrate beyond the surface in the presence of a thick smear layer formation, incorporating it into a hybridized smear layer.\textsuperscript{28} A very thin true hybrid layer may also form underneath this layer.\textsuperscript{28}

In the present study, the resin-dentin interdiffusion zone observed with the single-bottle bonding agents demonstrated the formation of a thick hybrid layer (4-5 μm), compared to a relatively thin layer (1-2 μm) for the self-etching primers. This morphological difference is believed to be due to acidity differences between the bonding systems. Single-bottle bonding agents are used with phosphoric acid with a pH <1.0, whereas Clearfil Liner Bond 2V primer has a higher pH of 2.0.\textsuperscript{30} Similarly, Miyasaka and Nakabayashi\textsuperscript{32} suggested that the depth of demineralized dentin depended on the concentration and application time of the acidic primer. The authors obtained the highest bond strengths with test specimens having a relatively thin hybrid layer of 1 μm. For this reason, the significantly higher bond strength value for CL-DC could not be explained on the basis of the hybrid layer thickness.

It has been demonstrated that the bond strength depends on hybrid layer mechanical properties rather than layer thickness.\textsuperscript{22,27} Therefore, the monomers must fully penetrate the exposed collagen network and fully polymerize in it to create an effective hybrid layer bond with etched dentin.\textsuperscript{26} Nonreinforced and exposed collagen fibrils were reported at the dentin-adhesive interface as a result of incomplete adhesive penetration into demineralized dentin with bonding systems requiring a separate acid treatment.\textsuperscript{29} Toledano et al\textsuperscript{26} reported that discrepancies between the depth of demineralization and the depth of resin infiltration were less likely to occur with self-etching primer systems, as both etching and priming occurred simultaneously. In the present study, despite the relatively thin hybrid layer formation, the higher bond strengths obtained with the self-etching primer system supported these findings. This result concurs with a previous study conducted by Yoshiyama et al.\textsuperscript{16} However, Mannocci et al\textsuperscript{26} found no significant differences between a single-bottle bonding agent and a self-etching primer. In that study, the single-bottle bonding agent was used in combination with 10% phosphoric acid rather than the 37% phosphoric acid used in the present study. It can be speculated that the mild etching effect that enables complete penetration of the single-bottle bonding agent into the demineralized post space dentin could be responsible for this difference.

The most remarkable finding of the present study is that a significantly higher bond strength was obtained with the light-polymerized bonding agent of the self-etching primer system, compared to the dual-polymerized bonding agent of the same system. Therefore, the
second hypothesis of this study, that dual-polymerized bonding agents result in greater bond strength compared to light-polymerized products, was rejected. This finding indicates that the light-polymerized bonding agent (Bond A) exhibited better mechanical properties than the dual-polymerized bonding agent (Bond A+B). According to Foxton et al., this result is related to the differences in the chemical compositions of Bond A and the mixture Bond A+B. Bond A contains photoinitiators and the acidic phosphate monomer MDP, whereas Bond B contains chemical initiators, but no MDP. When Bond A and Bond B were mixed, the concentrations of MDP and photoinitiators were decreased, which can result in a reduction in photopolymerization and bonding ability. The SEM observations of the present study revealed short and sparsely formed resin tags for CL-DC, which indicated insufficient penetration of the resin monomer into dentinal tubules, probably the result of lower monomer concentration. Additionally, Braga et al. demonstrated that dual-polymerized resins were extremely dependent on photopolymerization to achieve an optimal degree of monomer-polymer conversion. The fact that no statistical difference was found between light- and dual-polymerized single-bottle bonding agents revealed that light exposure from the cervical end of the post space could sufficiently polymerize the single-bottle bonding agents in the apical third of the post space. This result can be explained by the very low film thickness and light sensitivity of the single-bottle bonding agents. It should also be noted that the light- and dual-polymerized single-bottle bonding agents used in the present study have similar chemical composition, and dual polymerization was achieved with a specially designed microbrush coated with chemical initiators.

The dentin bonding agents in the present study were light polymerized before applying the resin luting agent and fiber post. After light polymerization, all dentin bonding agents tested could form a hybrid layer that did not interfere with the post placement into the post space. This is likely due to the fact that the dentin bonding agents tested produced a very low film thickness. Another cementation protocol for translucent fiber posts includes simultaneous light polymerization of the dentin bonding agent and the resin luting agent after the placement of the fiber post. This might be a more reliable method to ensure complete seating of the fiber posts. However, a previous SEM study demonstrated that this method may result in a reduced hybrid layer and resin tag formation, especially in the apical third of the post space dentin. The authors considered possible damage to the nonpolymerized adhesive film during the placement of the resin luting agent and the fiber post into post space. The type of resin luting agent and the application technique used to place the post seemed to be important factors that may have affected the complete seating of fiber posts into post spaces.

The luting agent Panavia F has the ability to adhere to different types of restorative materials, including fiber posts, because it contains the adhesive monomer (MDP). However, the anaerobic reaction of Panavia F’s chemical monomer component may cause premature polymerization in the apical region of the post spaces prior to insertion of a post. This is especially important when a resin luting agent is introduced into post spaces with a lentulo spiral instrument, as was done in the present study. The application of the resin luting agent with a lentulo spiral instrument may be an effective technique for reducing voids and bubbles within the luting agent. No sign of premature polymerization prior to post insertion was observed in the present study. This could be related to the fact that the dual-polymerized resin luting agent used provided sufficient working time, even in an anaerobic environment such as a post space.

According to the results of this study, the third hypothesis, that the bond strength may vary among the different regions of the post space dentin, is partially rejected. A significant decrease in bond strength was found only for the single-bottle bonding agents in the apical region of the post space, whereas the bond strength along the entire post space was similar for the self-etching primer system. It is not believed that this decrease is due to difficult handling characteristics encountered when placing adhesive materials in the apical region of the post spaces. Previous studies have also demonstrated the effective use of a microbrush in reaching the depths of prepared post spaces, resulting in the formation of uniform hybrid layers, even in the apical third. Consequently, decreased tubule density in the apical region of the post space might be a possible explanation.

Resin tags resulting from adhesive penetration into the dentinal tubules have been reported as an important factor in the adhesive-dentin bond, contributing about 30% to the total bond strength. Previous SEM investigations demonstrated that the mechanism for adhesive bonding to root dentin is based on resin tag formation. These findings seem to suggest that if there are fewer tubules per mm² in the apical region, the bond strength will be lower since there will be less resin tag formation. The SEM observations in the present study confirm this suggestion. It was observed that fewer and shorter resin tags formed with the single-bottle bonding agents in the apical third of the post space.

The correlation between the tubule density of the post space dentin and the bond strength of the single-bottle bonding agents was also noted in previous studies performed by Bouillaguet et al., Goracci et al., and Kurtz et al. However, results of the present study do
The strength of the bond in different post space dentin regions is complex, influenced by tubule density and the area of atubular dentin, as well as the type and chemical composition of the dentin bonding agents. As demonstrated in the present study, component variations in the chemical composition of the self-etching primer system resulted in different bond strength values and also caused alterations in the bonding mechanisms of the self-etching primer system. It should be noted that there may be limitations to the direct application of the results of the present study to clinical situations. One limitation is the absence of thermal cycling or cyclic loading, which may provide additional information about the durability of the adhesive bonding. It has been reported that unfiltered collagen fibrils between the hybrid layer and unetched dentin may be susceptible to long-term bond degradation due to slow hydrolysis of the exposed fibrils. The bonding agents selected for each bonding system in the present study were representative of a broad range of products within each category. As only a limited number of products for each dentin bonding system were tested, global statements regarding all products within a category cannot be made with certainty. However, it is expected that the general trends and concepts developed in this research may be valid for a number of products within a given category.

CONCLUSIONS

Within the limitations of this study, the following conclusions were drawn:

1. Compared to the single-bottle bonding agents, the system with a self-etching primer and a light-polymerized bonding agent provided significantly higher bond strength to post space dentin ($P<.001$) with a relatively thin hybrid layer.

2. The strength of the bond to the post space dentin was not dependent on the hybrid layer thickness.

3. Dual polymerization did not improve the bond strength values for the single-bottle dentin bonding agents ($P=.967$). The dual-polymerized bonding agent resulted in significantly lower bond strength ($P<.001$) in combination with self-etching primer.

4. The bond strength values with single-bottle bonding agents decreased significantly in the apical post space dentin ($P<.001$). This correlated with decreased tubule density and resin tag formation in the apical region of the post space.

5. Self-etching primer specimens demonstrated similar bond strength values in cervical, middle, and apical regions of the post space. Bond strengths for these specimens did not correlate with tubule density.

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