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Morphological and bond strength evaluation of different resin cements to root dentin

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This study correlated the morphological characteristics with the bond strengths of various resin cements used for bonding fiber posts to root canal dentin. Fifty glass-fiber posts (FRC Postec Plus) were luted into the root canals of extracted human anterior teeth using five resin cements (n = 10): Panavia F 2.0, PermaFlo DC, Variolink II, RelyX Unicem, and Clearfil Core. Before insertion of the post, the adhesive systems were labeled with fluorescein and the resin cement was labeled with rhodamine isothiocyanate. The roots were sectioned into three slices (of 2 mm thickness), and each slice was analyzed using confocal laser scanning microscopy in dual fluorescence mode to determine hybrid layer thickness, the number of resin tags, and the number of broken tags. Bond strengths were measured using a micro push-out test. Bond strengths to root canal dentin, as well as the morphological characteristics, were significantly affected by the materials. However, these factors did not correlate. The self-adhesive resin cement, which showed the formation of a hybrid layer and resin tags only sporadically, had the highest bond strengths. These results indicate that chemical interactions between the adhesive cement and hydroxyapatite may be more crucial for root dentin bonding than the ability of the same material to hybridize dentin.

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The restoration of endodontically treated teeth with fiber-reinforced composite posts has been studied intensively *in vitro* using fracture load evaluation (1) and bond strength testing of resin cements to the post surface (2) as well as to the root canal dentin (3–7). These studies demonstrated differing results regarding the investigated resin cements. Controlled randomized clinical trials that focus on the performance of fiber posts are rare (8–10). Clinical failures were caused by fractures of fiber posts as well as by loss of retention (11). Bonding to root canal dentin is hampered by limited visibility, anatomical features (12), and a comparably high configuration factor inside the root canal (13), and was found to be less effective than bonding to coronal dentin. Consequently, analysis of correlations between the morphological characteristics of the root dentin–adhesive interface and bond strength might identify weaknesses of adhesive systems with respect to the bonding behavior inside the canal.

Confocal laser scanning microscopy (CLSM) has been used in adhesive dentistry to visualize the micromorphologic characteristics of the dentin–adhesive interface (14). This method allows specimens to be studied without vacuum in a humid environment. The application of multiple fluorescent dyes and use of the dual fluorescence mode has been suggested for investigating the distribution of primer and adhesive inside the hybrid layer and the dentinal tubules (14, 15), and for nanoleakage analyses (16, 17). A recently published investigation revealed comparable results for hybrid layer measurements obtained using scanning electron microscopy (SEM) and CLSM on identical specimens after luting fiber posts into the root canal (18). The CLSM method provided more detailed information regarding the penetration and distribution of resin cement and adhesive than did SEM imaging.

The first aim of the present study was to analyze the morphological characteristics of the resin–dentin interface of five different resin cements and the corresponding adhesive systems with respect to the thickness of the hybrid layer, the penetration of adhesive and resin cement into the dentinal tubules, and the number of fractured resin tags. The second aim of the study was to investigate the bond strengths of the microscopically analyzed samples using micro push-out tests in order to identify any correlations between the morphological characteristics and the bond strengths. The null hypothesis of the present study was that neither morphological characteristics nor bond strength measurements are affected by the various materials investigated.

Material and methods

The crowns of 50 extracted human upper central anterior teeth were cut off at the cemento–enamel junction using a diamond blade under constant water cooling. Root canal preparation was performed at a working length of −1 mm from the apical foramen using FlexMaster rotary instruments (VDW, Munich, Germany) with a crown-down technique. Apical enlargement was performed to size 0.02/50, and the teeth were filled by means of cold lateral condensation using gutta percha points (VDW) and AH plus (DeTrey Dentsply, Konstanz, Germany) as a sealer. The samples were randomly divided into five groups of 10 teeth each and were stored in water for 24 h. Then, the root canals of each sample were enlarged using a low-speed drill provided by the manufacturer of the selected post system (FRC Postec Reamer Size 3; Ivoclar Vivadent, Schaan, Liechtenstein). All specimens were prepared by one practitioner using a standardized procedure; the depth of the post space preparation was 12 mm. After preparation, the post space was irrigated with 0.2% chlorhexidine solution (Pharmacy of Charité–Universitätsmedizin, Berlin, Germany).

FRC Postec Plus posts size 3 (Ivoclar Vivadent) were tried in and inserted with the following five different resin cements, according to the manufacturers' instructions: (i) Panavia F 2.0 (Kuraray, Osaka, Japan); (ii) PermaFlo DC (Ultradent, Salt Lake City, UT, USA), (iii) Variolink II (Ivoclar Vivadent); (iv) RelyX Unicem (3M ESPE, Seefeld, Germany); and (v) Clearfil Core (Kuraray) (Table 1). Before insertion of the posts, the adhesive systems were labeled with 0.1% sodium fluorescein (FNa; Sigma Aldrich, Steinheim, Germany) and applied onto the conditioned post surfaces (37% phosphoric acid, Total Etch; Ivoclar Vivadent) as well as onto the root canal dentin using a microbrush tip (Microbrush International, Grafton, WI, USA).

For the materials investigated that required the use of phosphoric acid, the etching gel (Total Etch; Ivoclar Vivadent) was applied using an endodontic syringe (Endoneedle; Vedefar, Dilbeek, Belgium) and washed out with water after 15 s. Excess water was removed using paper points, and the adhesive systems were applied with a microbrush tip. The resin cement was labeled with 0.1% rhodamine-isothiocyanate (RITC; Sigma Aldrich, St Louis, MO, USA) and applied onto the surface of the posts as well as into the orifice of the root canals using a small spatula. The posts were inserted into the canal, and surplus resin cement was removed. For the dual-curing systems, air block gel (Panavia F Oxyguard; Kuraray) was applied, and light curing was performed using a halogen curing-light (1200 mV cm^{-2}; Astralis 10; Ivoclar Vivadent) for 30 s.

After 24 h of water storage at 37°C, the tip of the post was fixed into an exactly fitting hole of a slide. Subsequently, the roots were cut into three slices (of 2 mm thickness) perpendicular to the long axis of the tooth by using a band saw (Exakt Apparatebau, Norderstedt, Germany). The first cut started 2 mm below the cemento–enamel junction; thus, the slices represented a coronal, a middle, and an apical location of the post space preparation. The slices were fixed onto slides and polished up to 4,000 grit (Exakt Mikroschleifsystem; Exakt Apparatebau).

Confocal laser scanning microscopy analysis (Leica TCS NT; Leica, Heidelberg, Germany) was performed in dual fluorescence mode using a 40× objective and a 2× electronic zoom. To minimize any cross-talk (i.e. the simultaneous scanning of moderately overlapping emission spectra of fluorescent dyes), sequential recording of both fluorescent dyes was performed with FNa (excitation: 488; emission: 525/50 band pass filter) and RITC (excitation: 568; emission: 890 long pass filter). The size of the images was $187 \times 187\ \mu m^2$ with a resolution of 1,024 × 1,024 pixels. Images were recorded at four standardized areas of each sample (19) and analyzed using IMAGEJ 1.35 S software (NIH, Bethesda, MD, USA). To quantify the thickness of the hybrid layer, measurements were made at four randomly chosen locations on each image, and the mean value was calculated (Fig. 1A). The numbers of dentinal tubules penetrated with adhesive and resin cement were counted. The penetration depths (μm) of the resin cements were analyzed using four scores: 1 = $< 3\ \mu$m; 2 = 3–8.9 μm; 3 = 9–15 μm; 4 = $> 15\ \mu$m. In addition, the number of broken tags on each image was counted.

After microscopic analyses, a 1-mm-thick slice was cut off each sample using a band saw (Exakt Apparatebau) and micro push-out testing was performed (Universal testing machine Zwick; Roell, Ulm, Germany) at a cross-head speed of 0.5 mm min^{-1}. With regard to the tapered design of the post, three different sizes of punch pins, as well as three different openings, were used for the push-out testing (5).

The maximum stress was calculated from the recorded peak load divided by the computed surface. In order to calculate the exact bonding surface, the tapered design of the posts with regard to the respective part of the post was considered. Therefore, each specimen was measured using a micrometer screw (Mitutoyo Messgeräte, Neuss, Germany), and the bonding surface was calculated using the formula of a conical frustrum:

$$\pi(R_1 + R_2)\sqrt{(R_1 + R_2)^2} + \mathrm{h}^2$$

After the push-out test, each specimen was examined under a stereomicroscope (DV 4; Zeiss, Jena, Germany) at 40× magnification to determine the failure mode. The specimens were divided into four groups according to the failure modes: (i) adhesive failures between post and cement; (ii) adhesive failures between dentin and cement; (iii) mixed failures; and (iv) cohesive failures inside the post. Furthermore, representative samples of the fracture modes of each group were studied using CLSM.

Statistical analysis was performed using SPSS version 14.0 software (SPSS, Chicago, IL, USA). The effects, on bond strengths, of materials and of their location inside the root canal were analyzed using two-way analysis of variance (ANOVA, Tukey-B *post hoc*). Comparisons between materials with respect to the morphologic characteristics (hybrid layer thickness, number of tags penetrated with adhesive and resin cement, number of broken tags, penetration depth of resin into dentinal tubules) were performed by calculating the mean values for each slice followed by analysis using the Kruskal–Wallis test and the Mann–Whitney *U*-test. A general linear model was used to analyze the influence of resin cement (factor) and number of broken tags (covariate) on bond strengths. The effects of the materials on the failure modes were investigated using the chi-square test. The level of significance was $\alpha = 0.05$ (two-sided).

Results

Bond strengths [mean and (standard deviation)] were affected by the resin cements used ($P < 0.001$), but not

Table 1

Composition of materials used according to material safety data sheet information

Luting agent	Bonding agent	Conditioning method	Manufacturer	Composition of primers	Composition of composite resins	Polymerization mode	Batch no.
Panavia F 2.0	ED primer	Self-etching primer	Kuraray	2-Hydroxyethyl methacrylate, 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP), *N*-methacryloyl-5-aminosalicylic acid, water accelerators	Sodium fluoride, 10-methacryloyloxydecyl dihydrogen phosphate, hydrophobic aromatic dimethacrylate, hydrophilic aliphatic dimethacrylate, silanated silica filler, silanated colloidal silica, DL-camphorquinone, initiators, silanated barium glass filler	Dual	41151
PermaFlo DC	PermaFlo DC primers A&B	H_3PO_4 (35%) 15 s	Ultradent	Ethyl alcohol, acetone	Bis-GMA, triethylene glycol dimethacrylate	Dual	BOHJS
Variolink II	Excite DSC	H_3PO_4 (35%) 15 s	Ivoclar Vivadent	HEMA, dimethacrylates, phosphoric acid acrylate, silica, ethyl alcohol	Bis-GMA, urethanedimethacrylate, triethylene glycoldimethacylate, ytterbium trifluoride, barium glass, silica	Dual	Variolink base: H34760; catalyst: H33170; excite: H09851
RelyX Unicem		Self-adhesive resin cement	3M ESPE	No primer available	Silica, glass, calcium hydroxide, methacrylated phosphoric acid ester, triethylen glycol dimethacrylate	Dual	256844
Clearfil Core	New bond	H_3PO_4 (35%) 15 s	Kuraray	10-Methacryloyloxydecyl dihydrogen phosphate, Bis-GMA, 2-hydroxyethyl methacrylate, hydrophobic aliphatic dimethacrylate, dibenzoyl peroxide, ethyl alcohol	Bisphenol A diglycidylmethacrylate, triethylene glycol dimethacrylate, glass filler, silica filler, colloidal silica	Chemical	Universal paste: 2590; catalyst paste: 2420; new bond: 41179

Bis-GMA, Bisphenol A diglycidylmethacrylate; HEMA, Hydroxyethyl methacrylate.

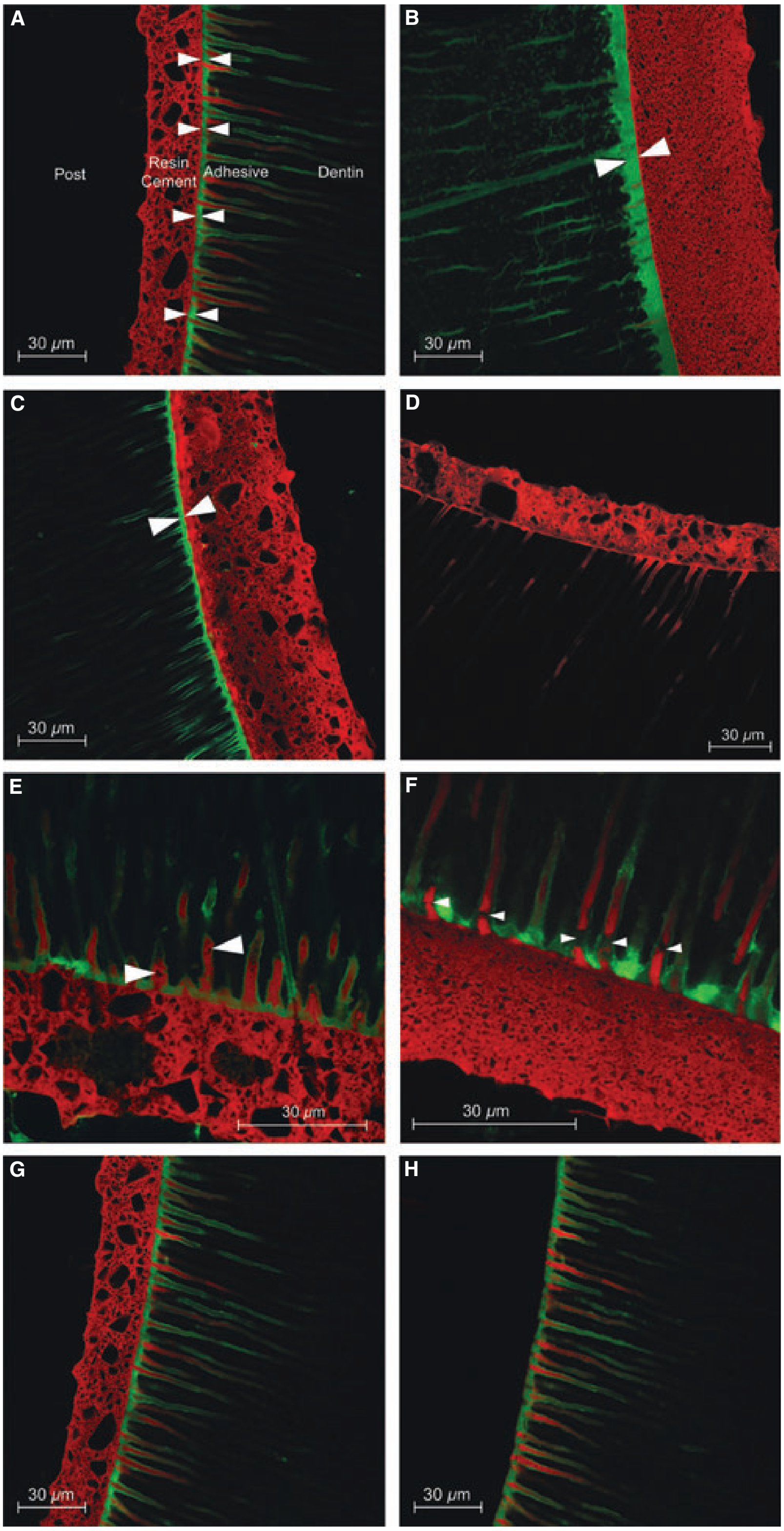

Fig. 1. (A) Representative confocal laser scanning microscopy (CLSM) image (Clearfil Core/New Bond) demonstrating post, resin cement, adhesive, and dentin, and indicating four points where the hybrid layer thickness was measured (arrows). (B) Representative sample showing the hybrid layer thickness of the materials PermaFlo DC, Panavia F/Ed Primer (C), and RelyX Unicem (D). Arrowheads demonstrate the thickness of the hybrid layer. No hybrid layer formation was detected for RelyX Unicem. (E) Representative sample of the material Variolink/Excite DSC, demonstrating the occurrence of fractured tags (arrowheads). (F) Representative sample of the material Clearfil Core demonstrating the penetration of filler particles of the resin cement into the dentinal tubules. (G) Representative sample of an adhesive failure mode of the material Clearfil Core before and after push-out testing (H) observed using CLSM.

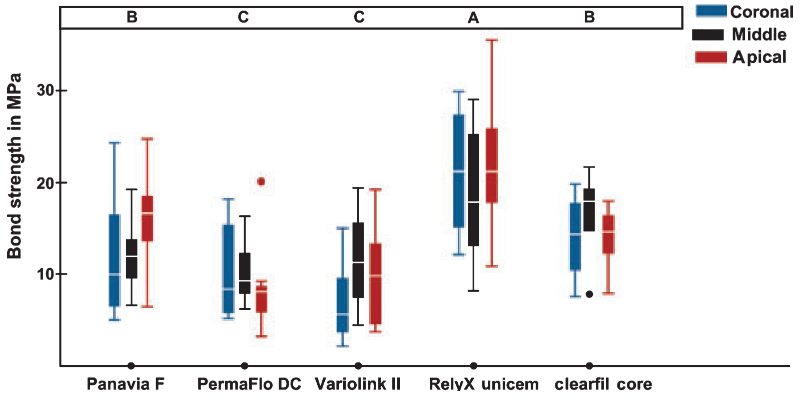

Fig. 2. Box-and-whisker plots, including medians and quartiles, indicating the bond strength values of the investigated materials with respect to the three locations (coronal, middle, and apical) inside the post space preparation. Different capital letters (shown above the plots) indicate significant differences between groups. Circles indicate outliers.

by the localization inside the root canal ($P = 0.435$). RelyX Unicem [20.4 (6.1) MPa] showed significantly higher bond strengths compared with Clearfil Core [14.9 (3.9) MPa] and Panavia F 2.0 [13.3 (5.3) MPa] ($P < 0.05$). PermaFlo DC [9.9 (4.2) MPa] and Variolink II [9.5 (5.0) MPa] were found to have significantly lower bond strengths than the other materials ($P < 0.05$). Figure 2 shows a box-and-whiskers plot representing the bond strengths of all materials investigated with respect to the coronal, middle, and apical localizations inside the root canal.

The thickness of the hybrid layer was significantly influenced by the factor 'resin cement' ($P < 0.001$). The hybrid layer thickness of PermaFlo DC [4.04 (2.1) μm] was significantly higher than that of the other resin cements ($P < 0.05$), whereas the hybrid layer thickness of RelyX Unicem was the lowest [0.07 (0.19) μm] of all the resin cements investigated (Table 2). Representative samples of hybrid layer formation of the resin cements are shown in Fig. 1B–D.

The number of dentinal tubules penetrated with adhesive was significantly affected by the materials ($P < 0.001$); use of Variolink II and Clearfil Core resulted in a significantly higher number of penetrated dentinal tubules than use of Panavia F and PermaFlo DC ($P < 0.05$). Use of RelyX Unicem was found to result in a significantly lower number of penetrated dentinal tubules compared with all other materials (Table 2).

Table 2

Analyses of the micromorphologic characteristics of the resin–dentin interface according to the following parameters: hybrid layer thickness, number of penetrated dentinal tubules (resin tags), and number of fractured tags

Material	Hybrid layer thickness (in μm)	Number of penetrated dentinal tubules (tags)	Number of fractured tags
Panavia F 2.0	1.2 (1; 1.6)^{B}	16.0 (12.7; 20.9)^{B}	0.0 (0.0; 0.0)^{A}
PermaFlo DC	3.4 (2.7; 4.3)^{D}	16.6 (13.8; 18.6)^{B}	0.6 (0.0; 1.8)^{C}
Variolink II	2.1 (1.8; 3.3)^{C}	27.8 (23.9; 30.0)^{C}	2.0 (0.7; 4.9)^{C}
RelyX Unicem	0.0 (0.0; 0.0)^{A}	1.0 (0.0; 2.3)^{A}	0.0 (0.0; 0.0)^{A}
Clearfil Core	2.7 (1.9; 3.1)^{C}	24.0 (22.1; 27.3)^{C}	0.0 (0.0; 0.5)^{B}

The data are presented as median values (25% and 75% quartiles). Same superscript letters indicate values that are not statistically different ($P > 0.05$; Mann–Whitney-U test; Bonferroni correction 10).

The percentage of tags infiltrated with resin cement, as well as their penetration depth, was significantly influenced by the resin cement ($P < 0.001$). Pairwise comparisons of these variables are given in Table 3. A representative sample of the penetration of resin cement into dentinal tubules, revealing filler particles, is shown in Fig. 1E.

The number of fractured tags was significantly affected by the materials ($P < 0.001$). For the materials RelyX Unicem and Panavia F, no fractured tags were observed. The materials PermaFlo DC and Variolink II resulted in a significant higher number of fractured tags compared with Clearfil Core ($P < 0.05$) (Table 2). A general linear model with the factor 'resin cement' and the covariate 'number of fractured tags' revealed a significant influence of the resin cements on bond strength ($P < 0.001$). The decrease in bond strength was 0.72 MPa for samples showing fractured tags. However, this influence was not significant ($P = 0.051$; 95% confidence interval = −0.03;

Table 3

Percentage of composite-filled tags with respect to all tags and the penetration depths of the resin cement presented in four scores

Material	Percentage of tags filled with resin cement	Penetration depths of resin cement (score)
Panavia F 2.0	61.0%^{A}	3–8.9 μm (2)^{B}
PermaFlo DC	74.8%^{B}	> 15 μm (4)^{C}
Variolink II	84.5%^{C}	9–15 μm (3)^{BC}
RelyX Unicem	100.0%^{D}	< 3 μm (1)^{A}
Clearfil Core	78.0%^{BC}	9–15 μm (3)^{BC}

Same superscript letters indicate values that are not statistically different ($P > 0.05$; Mann–Whitney-U test; Bonferroni).

Table 4

Analyses of failure modes for all materials investigated

Material	Failure mode (%)			
	Adhesive post/cement	Adhesive dentin/cement	Mixed	Cohesive post
Panavia F 2.0	36.7	46.7	16.6	0
PermaFlo DC	30.0	40.0	30.0	0
Variolink II	6.7	80.0	13.3	0
RelyX Unicem	43.3	10.0	33.3	13.4
Clearfil Core	0	90.0	10.0	0

1.44 MPa). A representative sample showing the occurrence of fractured tags is given in Fig. 1F .

The analyses of failure modes are presented in Table 4. The failure mode was significantly affected by the materials ($P < 0.001$; Chi-square test). A representative example of adhesive failure between dentin and cement (Clearfil Core), observed using CLSM, is shown in Fig. 1G,H. Here, the failure mode was localized between the hybrid layer and the resin cement, and, using the stereomicroscope, this failure was identified as an adhesive failure between dentin and cement.

Discussion

The null hypothesis of the present study was rejected because bond strengths to root canal dentin, as well the morphological characteristics of the resin–dentin interface, were obviously affected by the resin cements used in this project.

The use of multiple fluorescent dyes, simultaneously analyzed in dual fluorescence mode, allows separate observation of the differently labeled components if the excitation and emission peaks are well separated (20). In the present investigation, the use of appropriate filters for the dyes RITC and FNa, and the sequential recording of both dyes, was applied to guarantee well-separated emission signals.

Because the mechanism of dye labeling is based on a simple mixing process rather than on covalent linkage, the risk of non-homogeneous dye distribution or of leaching of the polar dye into the hydrophilic dentin, cannot be completely excluded (20, 21). However, the fluorescence of the recorded microscopic images was uniform. Thus, homogeneous distribution of the dyes could be assumed. An investigation previously carried out on the correlation of SEM and CLSM analyses reported preliminary test results on dye selection for CLSM imaging (18). The FNa-labeled adhesive showed no diffusion into the red-labeled (RITC) composite and there was a clear distinction between the dyes. Moreover, measurements of the hybrid layer using CLSM and SEM showed comparable results, thus validating the CLSM method.

An effect of the dyes on polymerization has previously been discussed (20). Depending on the dye concentration, fluorescent dyes should have the potential to reduce conversion of the bonding agent monomer as well as the bond strengths of materials to their substrates (22). Nevertheless, bond strength values of the various materials to the root canal dentin, measured in the present investigation, were similar to those reported in a previous study (5).

Hybridization of dentin was only detected sporadically for the material RelyX Unicem. This finding corroborates the results of investigations conducted previously that also described a superficial morphological interaction (3, 23, 24). The adhesive properties are claimed to be based upon acidic monomers that demineralize and infiltrate the tooth substrate, and create micromechanical retention and chemical adhesion to hydroxyapatite (3M ESPE RelyX Unicem product profile). In the present investigation, penetration of this cement into the dentinal tubules was found in only a few specimens. It can be concluded therefore that the smear layer did not dissolve consistently at the dentin–RelyX Unicem interface. The rapid rise in pH could also affect the demineralization effect of this material (25). Moreover, a recent investigation documented an intense chemical interaction of RelyX Unicem with hydroxyapatite (26).

In contrast to microtensile bond strength testing, the push-out design showed (i) no premature failures and (ii) an acceptable variability of the data distribution (4).

The light-transmitting ability of fiber posts and the complete polymerization of the resin cement in the apical part of the root have been questioned previously (27). On the one hand, data indicated that some light was transmitted through the fiber posts at a depth of 10 mm (28), but, on the other hand, it was shown that the hardness of a resin-based composite 6 mm from the head of the post is much less than at 2 mm, even with the use of a translucent post (29). This was confirmed by another study that revealed a constant reduction in the degree of conversion of fiber-reinforced composite with increased length of simulated root canals (30). A recently published investigation reported a decrease in light intensity, coronally to apically, of translucent fiber posts, which could affect the curing efficacy of resin composites in the depth of the root canal (31). This was also demonstrated for the FRC Postec Plus post used in the present investigation (31). However, the bond strengths were not affected by the location inside the post-space preparation in the present investigation, which is in accordance with the results of previous studies (4, 32, 33). By contrast, other studies reported a significant influence of the region inside the canal on bond strength (5, 6, 34). This leads to the assumption that the application procedure of the cements within the narrow and deep root canal is difficult to control (32).

The differences observed in bond strengths of the resin cements investigated are in accordance with the outcome of a previously conducted study (5). However, other studies revealed lower bond-strength values for the self-adhesive resin cement RelyX Unicem (3, 4, 32). A recently published study found no significant differences in μTBS (microtensile bond strength) between RelyX Unicem and Panavia F to enamel and to crown dentin (24). Close adaptation of the cement to the cavity wall was only ensured after using some pressure during application (24). By inserting fiber posts, pressure is also applied. Thus, the results of the mentioned study do support the present results. The adhesives used with Panavia F and Clearfil Core both contain the phosphate-based functional monomer 10-MDP. This molecule has been found to form chemical interactions with hydroxyapatite remaining around the collagen within the hybrid layer (35), and because of the low solubility in of the MDP-calcium salt in water, this bond is expected to be stable (36). Lower bond strength has been measured for Variolink II and PermaFlo DC, even though Variolink II was applied using special endo-microbrushes coated with initiator particles to ensure polymerization of the adhesive inside the canal. Similar results have been observed previously for Variolink II (4, 5, 32). It is recommended that etch-and-rinse alcohol-based and acetone-based adhesives should be applied on moist dentin following the 'wet-bonding' technique (37). The degree of moisture is difficult to control inside the root canal. Moreover, the auto-curing potential of Variolink II has been shown to be inferior compared with other dual-cure cements (38), which is an important fact for the use of this material inside the root canal. The lower bond strength of Variolink in the coronal part of the root canal compared with the other parts contradicts previously published results (5, 32) and should therefore not be overestimated because this difference was not statistically significant and no overall effect of the location on bond strength could be found.

The analysis of failure modes revealed that the predominantly occurring failure mode was adhesive between dentin and cement, which is in accordance with the results of a recently published investigation (32). The self-adhesive resin cement RelyX Unicem was the only material that demonstrated some 'cohesive failures inside the post'. In these cases, bond strength to the dentin, as well as to the post, was higher compared with the stability of the post itself. In general, bond strength to root canal dentin is lower than bond strength to coronal dentin. Numerous *in vitro* and *in vivo* studies have reported adhesive failures predominantly between dentin and cement (5, 6, 9, 10, 32). This is also supported by the present results.

Confocal laser scanning microscopy analysis of representative samples of 'adhesive failures between dentin and cement' identified a separation between the hybrid layer and the underlying resin cement. It can be argued that the connection between resin cement and demineralized and infiltrated root canal dentin might be a frailty of the resin–dentin interface (39). The observed failure mode could rather be described as cohesive inside the resin–dentin interdiffusion zone. However, in the present study only a limited number of samples were additionally observed using CLSM, whereas the failure mode analysis was conducted exclusively using the stereomicroscope.

Bond integrity inside the root canal is challenged by the limited capacity to dissipate polymerization shrinkage stresses in long narrow post spaces exhibiting a highly unfavorable configuration factor (13). The present investigation did not reveal any visible gaps inside the resin–dentin interface. However, broken resin tags were found for the investigated materials that required the application of phosphoric acid before application of the adhesives (Fig. 1F). In addition, these systems demonstrated higher penetration depths of the resin cements into the dentinal tubules than the self-adhesive systems. Fractured tags could have occurred as a result of the extensive demineralization produced by the application of phosphoric acid, the penetration of resin cement inside the dentinal tubules, and polymerization shrinkage stresses. A significant influence of the covariate number of fractured tags on bond strength could not be verified in the present investigation; however, a tendency was observed for bond strength reduction in samples with a high number of fractured tags. The clinical relevance of this reduction seems to be negligible, but further research is necessary to confirm this assumption.

It can be concluded that the application of adhesive systems which require the use of phosphoric acid resulted in uniform hybrid layers and large numbers of penetrated dentinal tubules filled with adhesive and resin cement. However, fractured tags occurred as a result of the use of these systems, and bond strengths were lower compared with those of the self-adhesive resin cement. Within the limitations of an *in vitro* study, this confirms the assumption that chemical interactions between the self-adhesive resin cement and hydroxyapatite may be effective inside the root canal.

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