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3D micro-CT analysis of void formation of glass fiber posts bonded using different resin cements

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Abstract

Aim: The aim of this in vitro study was to evaluate and compare the void volumes at the dentin-post interface when glass fiber posts were bonded using different resin cements, as assessed by 3D micro-computed tomography (μCT).

Methodology: For this investigation, thirty extracted human maxillary central incisors with a single root were chosen. The specimens were divided into three groups at random ($n = 10$) and restored with glass fiber posts that were cemented using Variolink N, Panavia F 2.0, and RelyX Unicem resin cements, respectively. A resolution of 13.7 μm was used for high-resolution μCT scanning to obtain detailed images of the specimens. The Kruskal-Wallis test (post hoc: Mann-Whitney U with Bonferroni correction), the Friedman test, and the Spearman rank correlation test ($\alpha = 0.05$) were used for statistical evaluation.

Results: μCT analysis revealed that the mean total void volume at the dentin-post interface was 1.67 ± 0.69 mm^3 for the Variolink N group, 2.59 ± 1.75 mm^3 for the Panavia F 2.0 group, and 3.28 ± 2.13 mm^3 for the RelyX Unicem group. The differences between the groups were statistically significant ($p < 0.05$), with the lowest void volume in the Variolink N group and the highest in the RelyX Unicem group. Within each group, void formation was distributed homogeneously across root levels ($p > 0.05$), whereas specimens cemented with RelyX Unicem showed significantly higher void formation in the apical third than the other two cements ($p < 0.05$). No correlation was found between empty canal volume or empty canal surface area and void volume ($p = 0.34$ and $p = 0.19$, respectively).

Conclusion: Post-cementation analysis revealed significant differences in total void volume among the resin cements, whereas within-group regional comparisons did not yield statistically significant differences. Decementation of fiber posts is frequently associated with voids within the luting cement layer, so the choice of resin cement and its delivery technique remains clinically relevant.

Keywords: Fiber post, resin cement, micro-CT, void formation, luting agent

Introduction

Teeth with extensive loss of structure require posts after endodontic treatment to restore function. Post-endodontic teeth are more prone to fractures compared to teeth with vital pulp (1, 2). Additionally, irrigant agents employed during root canal treatment interact with dentin, inducing alterations in its physical properties (3). Since pulp tissue is removed during the endodontic procedure, a loss of proprioception occurs, resulting in a devitalized tooth that is subject to greater loads than one with vital pulp (3, 4).

The primary function of an intraradicular post is to retain the core when the remaining coronal structure is insufficient; a post does not intrinsically reinforce an endodontically treated tooth. Accordingly, preservation of residual dentin and an adequate ferrule are major determinants of long-term prognosis (5, 6). Glass fiber posts have an elastic modulus closer to that of dentin than metallic posts and may promote more favorable stress distribution and failure patterns. However, systematic-review evidence has not demonstrated a significant difference in clinical root-fracture incidence between metal and fiber posts, emphasizing that post selection alone does not determine prognosis (6, 7). Debonding nevertheless remains a frequent technical complication of adhesively luted fiber posts (6, 8).

When there is considerable loss of coronal tooth structure following endodontic treatment, post application is preferred (9-11). This process involves the removal of hard tissue to create a post cavity (12, 13). It is essential to quantify the amount of hard tissue removed at each stage of tooth restoration. Such quantification is utilized to assess the extent of hard tissue removal during endodontic treatment and to evaluate the volumetric changes before and after post cementation following the preparation of the root canal post cavity (13, 14).

Resin cements are used to enhance post retention because loss of retention and debonding are frequent technical complications (13, 15). Their clinical behavior depends not only on material-related properties such as sorption and solubility, but also on the integrity of the luting layer (16). Although cement thickness has been extensively investigated, fewer studies have quantitatively assessed voids and gaps within the post-cement-dentin complex. These defects cannot be adequately characterized by conventional two-dimensional methods, whereas micro-CT permits non-destructive volumetric evaluation (17-19).

Durable intraradicular adhesion remains technique-sensitive because the confined canal geometry, high configuration factor, limited access and moisture control, smear-layer and sealer remnants, and reduced light transmission toward the apex can compromise resin polymerization and interfacial integrity (6, 8). Voids and gaps reduce the effective bonded area and may create stress-concentration sites or potential pathways for fluid movement; their occurrence is influenced by post adaptation, cement rheology, mixing, and the method of cement delivery (8, 17).

Micro-computed tomography is a high-resolution, non-destructive three-dimensional imaging method that allows the same specimen to be scanned repeatedly before and after an intervention. This enables within-specimen registration and quantitative morphometry without sectioning-related tissue or material loss (18-22). Depending on voxel size and the segmentation protocol, micro-CT can quantify canal and material volumes, surface area, dentin thickness, prepared and unprepared surfaces, canal transportation, polymerization shrinkage, and the number, volume, distribution, and connectivity of voids or gaps (18-22). In post-cementation studies, differences in X-ray attenuation can be used to reconstruct the post-cement-dentin complex and analyze defects separately in the coronal, middle, and apical thirds.

Nevertheless, micro-CT measurements are method-dependent and may be influenced by voxel size, gray-value threshold selection, partial-volume effects, beam-hardening and ring artifacts, specimen movement, and reconstruction or filtering settings; standardized acquisition and segmentation procedures are therefore essential for reproducibility (21, 22). Moreover, micro-CT provides structural information rather than a direct measure of bond strength, leakage, or biological activity, so volumetric void analysis should be interpreted as complementary to mechanical and biological assessments.

The aim of this research article was to evaluate the volumetric voids in teeth cemented with different resin cements by employing high-resolution micro-computed tomography (micro-CT, μCT).

Materials and Methods

Ethical approval

This study was approved by the Adıyaman University Non-Invasive Clinical Research Ethics Committee (protocol number: 2024/5-14). All procedures were performed in accordance with relevant guidelines and regulations, including the Declaration of Helsinki.

Sample size calculation

Based on a similar study, the sample size was calculated using G*Power 3.1.9.4 software (Heinrich Heine University, Düsseldorf, Germany). An a priori power analysis (F tests; ANOVA: fixed effects, omnibus, one-way) was performed, assuming an effect size of $f = 0.75$, a significance level of $\alpha = 0.05$, and three experimental groups. The study included 30 specimens, with 10 specimens allocated to each group. Under these parameters, the calculated actual statistical power was approximately 94.5%.

Sample selection

Thirty human maxillary central incisors were used in this investigation. Initially, these teeth were mechanically debrided with hand scalers to remove surface debris, and subsequently immersed in formaldehyde. Throughout the study, the specimens were stored in Hanks' balanced salt solution. Inclusion criteria included human maxillary central incisors (including those with periodontal involvement), while teeth with developmental anomalies, calcifications, fractures, caries, or external cracks were excluded. All procedures were conducted at a controlled temperature of 23 ± 2 °C.

Experimental procedures and groups

To standardize the root canal length, the crowns of the teeth were sectioned perpendicularly to their long axis using a diamond bur (Horico, Hopf, Ringleb & Co., Berlin, Germany) under water cooling. Radiographs were obtained in both bucco-lingual and mesio-distal projections to verify the root canal configuration at a distance of 10 mm from the apex. Prior to instrumentation, silicone (Zhermack SpA, Badia Polesine, Italy) was applied to cover the apical foramen of each tooth, thereby preventing the outflow of fluids and debris. The specimens were subsequently scanned using micro-computed tomography (μCT) prior to the creation of the endodontic access cavity (Fig. 1).

To prepare endodontic access cavities, a round bur (Horico, Hopf, Ringleb & Co., Berlin, Germany) was used. An endomotor (Endo-Mate TC2, NSK Nakanishi Inc., Tochigi, Japan) and ProTaper Universal rotary Ni-Ti files (Dentsply Maillefer, Ballaigues, Switzerland) were used in the crown-down method to prepare the root canal, keeping the working length 0.5 mm short of the apical foramen. Between file changes, the root canals were irrigated with saline, debrided for one minute with 0.5% sodium hypochlorite, and then washed with distilled water. Following paper point drying (DiaDent Group International, Cheongju, Korea), gutta-percha (gutta-percha points, DiaDent Group International, Cheongju, Korea) and AH 26 root canal sealer (Dentsply DeTrey, Konstanz, Germany) were used to obturate the canals. The specimens were then kept for a week at 37 °C and 100% humidity.

After canal preparation and obturation, post cavities were prepared using a Snowpost 1.2 bur (Carbotech, Ganges, France) equipped with 9 mm stoppers until the desired working size was achieved, replacing the burs after every five teeth to ensure consistency. After cleaning and drying the post space, 35% phosphoric acid (Ultra-Etch, Ultradent Products Inc., South Jordan, UT, USA) was applied to the root dentin for 15 seconds, followed by a 1-minute water rinse and drying. The post space was then verified in all specimens using a periodontal probe.

All specimens were scanned using a μCT scanner (SkyScan 1172; Bruker-microCT, Kontich, Belgium) before cementation. With a pixel resolution of 13.7 μm, the scanning parameters were adjusted at a 0.5 mm Al+Cu filter, an operating voltage of 85 kV, and a current of 118 μA. With a camera exposure period of 930 ms, a rotation step of 0.5°, an average of 3 frames per location, and a random movement of 20, the scanning procedure comprised a 360° revolution around the vertical axis. A total of 60 minutes was spent scanning each specimen. The resulting 8-bit TIFF images were converted into axial sections using NRecon v.1.6.3 software (Bruker-microCT, Kontich, Belgium) (Fig. 2).

The prepared post gaps were cemented as described below:

Group 1 (Variolink N):

After being examined, the posts were etched for 60 seconds using 35% phosphoric acid, cleaned, and dried. With no additional post manipulation, silane (Monobond Plus, Ivoclar Vivadent, Schaan, Liechtenstein) was then applied and left to react for 60 seconds before drying. Following 15 seconds of priming (Syntac Primer, Ivoclar Vivadent, Schaan, Liechtenstein) and drying, a bonding agent (Syntac Adhesive, Ivoclar Vivadent, Schaan, Liechtenstein) was applied to the canal walls for 10 seconds and allowed to cure. Both the canal walls and the posts were coated with Heliobond (Ivoclar Vivadent, Schaan, Liechtenstein), which was then gently dried. A 1:1 mixture of the base and catalyst pastes of the resin cement (Variolink N, Ivoclar Vivadent, Schaan, Liechtenstein) was then prepared, applied to the surface of the post, and introduced into the canal using a lentulo spiral. Finally, the post was seated in the canal and polymerized with a light-curing unit (LED.C, Guilin Woodpecker Medical Instrument Co., Ltd., Guilin, China) for 40 seconds.

Group 2 (Panavia F 2.0):

The posts were cleaned and dried with alcohol, then treated with silane (Monobond Plus, Ivoclar Vivadent, Schaan, Liechtenstein). The cement (Panavia F 2.0, Kuraray Noritake Dental Inc., Tokyo, Japan) was applied directly into the canal using an in-canal tip, and the post was inserted into the post cavity within 40 seconds. Polymerization was achieved by exposing all surfaces to a light-curing unit (LED.C, Guilin Woodpecker Medical Instrument Co., Ltd., Guilin, China) for 20 seconds each. The material was allowed to chemically set for an additional 5 minutes.

Group 3 (RelyX Unicem):

The posts were cleaned and dried with alcohol. Silane (Monobond Plus, Ivoclar Vivadent, Schaan, Liechtenstein) was applied, and the cement (RelyX Unicem, 3M ESPE, Seefeld, Germany) was mixed and inserted into the canal using a lentulo spiral. The post was then placed into the canal with the cement and secured within the post cavity within 40 seconds. All surfaces were polymerized using a light-curing unit (LED.C, Guilin Woodpecker Medical Instrument Co., Ltd., Guilin, China) for 40 seconds.

Three-dimensional visualization and qualitative assessment of void formation used CTVol v.2.2.1 software (Bruker-microCT, Kontich, Belgium) for three-dimensional visualization and qualitative assessment of void formation, which provided measurements of the regional volume of each specimen as well as the surface area and volume of each gap between the dentin and the post (Fig. 3).

Statistical analysis

All analyses were performed using SPSS 25 (IBM SPSS Statistics for Windows, Version 25.0, IBM Corp., Armonk, NY, USA). The significance level was set at $\alpha = 0.05$.

Because the data were not normally distributed (Shapiro–Wilk test, $p < 0.05$), nonparametric tests were used to assess group differences. For overall comparisons, the Kruskal–Wallis test was employed, and the Mann–Whitney U test with Bonferroni correction was utilized for pairwise comparisons when significance was determined. Regional void volumes within each group (apical, middle, and coronal thirds of the same specimen) were compared using the Friedman test. Correlations between empty canal volume or empty canal surface area and void volume were assessed using the Spearman rank correlation test.

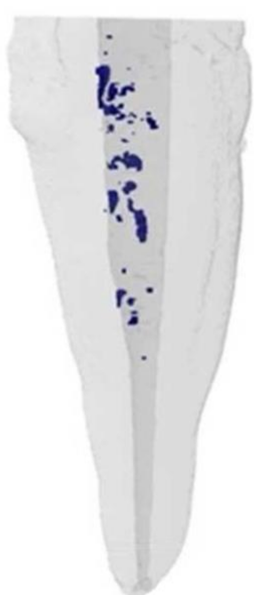

Figure 1. Preoperative micro-computed tomography visualization of the post space volume.

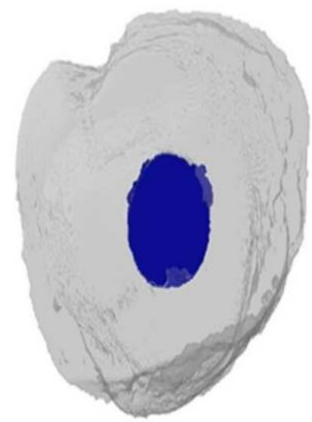

Figure 2. Post-cementation post space volume assessment using micro-computed tomography.

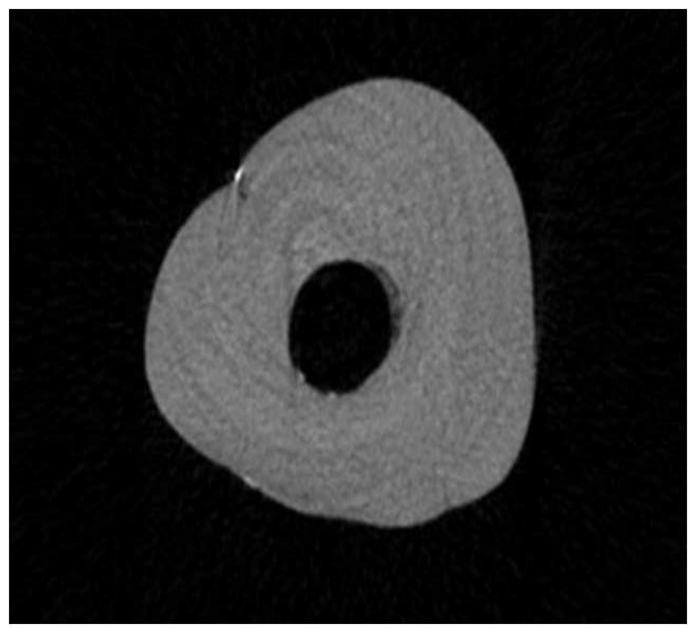

Figure 3. Micro-computed tomography imaging of the root with post volume analysis.

Results

The mean empty canal volumes for the Variolink N, Panavia F 2.0, and RelyX Unicem groups were 16.41 ± 3.17 mm^3, 20.90 ± 4.15 mm^3, and 15.75 ± 3.04 mm^3, respectively, with an overall mean volume of 17.69 ± 4.10 mm^3 (Table 1). The mean empty canal surface areas were 51.33 ± 4.87 mm^2, 61.01 ± 9.63 mm^2, and 47.12 ± 7.43 mm^2 for the Variolink N, Panavia F 2.0, and RelyX Unicem groups, respectively, with an overall mean surface area of 53.15 ± 9.39 mm^2 for all three groups combined (Table 2). The volumes of the cavities remaining after cementation of the posts were 1.67 ± 0.69 mm^3, 2.59 ± 1.75 mm^3, and 3.28 ± 2.13 mm^3 for the Variolink N, Panavia F 2.0, and RelyX Unicem groups, respectively (Table 3).

Total void volume differed significantly between the cement groups ($p < 0.05$), being lowest with Variolink N and highest with RelyX Unicem. Moreover, no correlation was observed between empty canal volume and void volume ($p = 0.34$) or between empty canal surface area and void volume ($p = 0.19$). Within each resin cement group, void formation was distributed homogeneously across the coronal, middle, and apical thirds ($p > 0.05$). When the same root level was compared between groups, however, specimens cemented with RelyX Unicem showed significantly higher void formation in the apical third than the other two cements ($p < 0.05$) (Table 3).

The mean void volumes (mm^3), standard deviations (SD), and median values for total and regional measurements across the resin cement groups are summarized in Table 3. A statistically significant difference was observed among the resin cement groups regarding total void volume ($p < 0.05$). The lowest total void volume was recorded in the Variolink N group (1.67 ± 0.69^a mm^3; Median: 1.10 mm^3), which was significantly lower than both the Panavia F 2.0 (2.59 ± 1.75^b mm^3; Median: 2.00 mm^3) and RelyX Unicem (3.28 ± 2.13^c mm^3; Median: 2.44 mm^3) groups ($p < 0.05$). The highest total void volume was exhibited by the RelyX Unicem group. Regarding the root regions: In the apical third, a statistically significant difference was detected among the cement groups ($p < 0.05$). RelyX Unicem (1.16 ± 0.75^b mm^3) demonstrated significantly higher void volume in the apical region compared to Variolink N (0.53 ± 0.35^a mm^3) and Panavia F 2.0 (0.86 ± 0.58^a mm^3) ($p < 0.05$). In the middle third and coronal third, no statistically significant differences were observed among the cement groups ($p > 0.05$).

Data normality was evaluated using the Shapiro-Wilk test. Inter-group comparisons among resin cements were performed using the Kruskal-Wallis test (post-hoc: Mann-Whitney U test with Bonferroni correction). For intra-group regional comparisons (apical, middle, and coronal thirds within the same tooth), the Friedman test was utilized. Statistical significance was set at $p < 0.05$.

Table 1. Mean empty canal volume of the groups (mm^3).

Group	n	Mean	SD
Variolink N	10	16.41	3.17
Panavia F 2.0	10	20.90	4.15
RelyX Unicem	10	15.75	3.04
Total	30	17.69	4.10

SD: Standard deviation

Table 2. Mean empty canal surface area of the groups (mm^2).

Group	n	Mean	SD
Variolink N	10	51.33	4.87
Panavia F 2.0	10	61.01	9.63
RelyX Unicem	10	47.12	7.43
Total	30	53.15	9.39

SD: Standard deviation

Table 3. Regional and total void volumes of the groups (mm^3).

Root region	Variolink N (n=10)		Panavia F 2.0 (n=10)		RelyX Unicem (n=10)	
	Mean ± SD	Median	Mean ± SD	Median	Mean ± SD	Median
Apical third	0.53 ± 0.35^a	0.41	0.86 ± 0.58^a	0.80	1.16 ± 0.75^b	1.03
Middle third	0.55 ± 0.51	0.27	0.82 ± 0.53	0.53	0.97 ± 0.74	0.64
Coronal third	0.59 ± 0.44	0.35	0.91 ± 0.64	0.53	1.15 ± 0.78	0.77
Total	1.67 ± 0.69^a	1.10	2.59 ± 1.75^b	2.00	3.28 ± 2.13^c	2.44

* Different superscript letters (a, b, c) in the same row indicate statistically significant differences between groups ($p < 0.05$).
SD: Standard deviation

Discussion

Post systems are employed to rehabilitate teeth with extensive loss of structure (9, 10). When posts are cemented to the tooth, cavities may form at the post-dentin cement interface depending on the cement utilized (23). Cavity formation is primarily attributed to air entrapment during the mixing process of the cement. Additionally, indirect cavity formation may occur due to the incorporation of small bubbles into the liquid material (23, 24). Analysis of our data reveals that, within each cement group, void formation was distributed uniformly across the root levels. However, the number of cavities in the apical third and the overall cavity formation were higher in specimens cemented with RelyX Unicem compared to those cemented with the other materials. Previous studies have demonstrated that hand-mixed conventional cements tend to contain more and larger voids than encapsulated or directly injected cements (23, 24). Although none of the three cements evaluated here required hand mixing on a pad, total void volume still differed between them, indicating that factors beyond the mixing method—such as cement viscosity and the delivery technique—also contribute to void formation.

Micro-CT studies have proven effective for evaluating the post-cement-dentin complex because they do not distort the specimens (25-27). The technique provides a three-dimensional visualization of the root canal contents and an exact simulation of the natural tooth model without compromising specimen integrity, thus yielding data that can be used in further research (28-30). Micro-CT enables the differentiation between resin cement, fiber post, and voids (24, 31), whereas optical coherence tomography has also been applied to assess void and gap formation in resin-based materials (32).

The study determined the volumes of voids remaining after post cementation to be 1.67 ± 0.69 mm^3, 2.59 ± 1.75 mm^3, and 3.28 ± 2.13 mm^3 for the Variolink N, Panavia F 2.0, and RelyX Unicem groups, respectively. Group comparisons indicated a statistically significant difference in total void volume ($p < 0.05$), with the lowest values in the Variolink N group. The injectable cement systems used in this study minimized gaps typically caused by manual mixing, eliminating the need for manual intervention. The overall low void volumes recorded in all groups are likely related to the use of these injection systems, although differences between the cements persisted.

Nevertheless, the observed regional differences might indicate that the integrity of the fiber post within the canal could be compromised, potentially facilitating microbial passage and leading to treatment failure. However, Uzun et al. (31) found no direct correlation between post region and push-out test results.

This study evaluated the void properties of various resin cements and their regional distributions using micro-CT. It has emerged as a powerful non-destructive three-dimensional analytical tool for visualizing cavity parameters. The results demonstrated that both total void volume and its regional distribution were influenced by the type of cement used. Rengo et al. (27) reported that most voids were located in the coronal part of posts cemented with resin, irrespective of void morphology, attributing this finding to the cement application method. In the present study, by contrast, void formation did not differ significantly between root levels within a given cement group; the coronal predominance reported by Rengo et al. (27) was therefore not reproduced, which may be explained by differences in post geometry and cement delivery between the two studies.

In summary, a certain degree of void formation was observed in all tested resin cements, and total void volume differed significantly between the groups.

Among the cements investigated, RelyX Unicem exhibited the highest void parameters when analyzed regionally. It is recommended that future studies conduct a more comprehensive examination of void formations in resin cement layers, with an emphasis on biological rather than solely mechanical aspects.

Conclusion

Within the limitations of this in vitro study, total void volume after cementation differed significantly among the three resin cements, being lowest with Variolink N and highest with RelyX Unicem. However, when analyzed by region, RelyX Unicem resin cement showed the highest void formation in the apical third, which may compromise the apical seal of the post-cement-dentin complex. Future studies with larger samples, including in vivo studies, are encouraged to confirm these findings and increase their generalizability. Furthermore, the formation of voids within the resin-cement layer should be examined more comprehensively from a biological rather than a mechanical perspective.

Disclosures

Ethical Approval: The study was approved by the Adıyaman University Non-Invasive Clinical Research Ethics Committee, in accordance with the ethical standards of the Declaration of Helsinki (protocol number: 2024/5-14).

Peer-review: Externally peer-reviewed.

Author Contributions: Conception — Z.G., A.B.; Design — A.B.; Supervision — H.Y.Y.K., N.S.A.K.; Materials — Z.G.; Data Collection and/or Processing — Z.G., A.B., H.Y.Y.K.; Analysis and/or Interpretation — Z.G., A.B., N.S.A.K.; Literature Review — Z.G., A.B., H.Y.Y.K.; Writer — Z.G.; Critical Review — Z.G., A.B., H.Y.Y.K., N.S.A.K.

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