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Retention of Manually or CAD/CAM-customized Fiberglass Posts Luted to Enlarged Root Canals with Different Resin Cements

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Clinical Relevance

Customized fiberglass posts decrease resin cement thickness and void formation, favoring higher retention in enlarged root canals.

SUMMARY

The aim of this laboratory study was to evaluate the pull-out force of a prefabricated fiberglass post (PP), relined fiberglass post (RP), or milled fiberglass post (MP) luted with Multilink N (MN), RelyX Unicem 2 (RXU2) or RelyX Ultimate (RU) to enlarged root canals. The thickness of the resin cements and the presence of voids in the resin cement film were observed. The root canals of 90 bovine incisors were enlarged, endodontically treated, and randomly divided into 9 groups (n=10) according to the post type and resin cement. The specimens were scanned using micro-CT to analyze the thickness of the resin cement and the presence of voids. The specimens were submitted to mechanical cyclic loading (500,000 cycles at 50 N load) and subjected to pull-out force testing. Two-way ANOVA and Tukey's test analyzed the pull-out force and resin cement thickness data. Kruskal-Wallis and Bonferroni tests analyzed

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the void scores. The interaction between factors (post x resin cement) was significant (*p*=0.0001) for the pull-out force. Higher pull-out forces were obtained for RP and MP compared to PP. The post factor was significant (*p*=0.0001) for resin cement thickness, which was higher for PP (1054 μm), followed by MP (301 μm) and RP (194 μm). More void formation occurred for PP, being less for RP, differing significantly among the posts. Post customization (RP and MP) decreased resin cement thickness and void formation, favoring a higher pull-out force. Resin cements requiring an adhesive application (MN and RU) favored higher pull-out force than self-adhesive resin cement (RXU2).

INTRODUCTION

Successful functional and aesthetic rehabilitation of endodontically treated teeth depends on the amount of structure remaining.[1] Root canal access and instrumentation lead to substantial loss of root dentin and often require an intraradicular retainer and a full crown restoration.[2] The function of the post is to promote retention and support for coronal tooth restoration.[1,2]

According to the literature, posts are classified as prefabricated or customized. The most commonly used prefabricated post is the fiberglass post, which has an elastic modulus similar to dentin and resin cement and allows a uniform stress distribution and absorption of stress along the root, minimizing the risk of fractures.[3,4] Fiberglass posts also have good aesthetic and optical properties that make them suitable for use in highly aesthetic regions.[5]

Laboratory studies have shown that the closer the post is to the root canal walls, the smaller the resin cement film and the greater the bond strength between the root and the resin cement.[6,7] Overprepared or large root canals present a great thickness of resin cement when prefabricated fiberglass posts are used, which results in increased polymerization shrinkage stress in the resin cement layer, contributing to the formation of bubbles, cracks, and spaces along the post interface.[7,8] These discontinuities reduce the retention of the fiberglass post and lead to subsequent debonding, which is the main reason for post failure.[9,10]

In an attempt to improve fiberglass post adaptation in large root canals, a technique was proposed consisting of relining the prefabricated post with a composite resin.[11,12] This technique provides good adaptation to the canal walls, facilitating a thin and uniform resin cement layer and greater retention.[12,13] However, manual customization produces multiple interfaces between the prefabricated post and composite resin, increasing the chances of failure.[14]

Recent studies have suggested the use of computer-aided design/computer-assisted manufacturing (CAD/CAM) systems for the customization of posts produced directly or indirectly. Zirconia posts were the first CAD/CAM fabricated. Although they present excellent aesthetics, the high elastic modulus of zirconia posts causes stress in root dentin, resulting in catastrophic root fractures.[15] Spina and others[16] tested a hybrid ceramic material, a nanoceramic resin composite, and an experimental fiberglass-reinforced epoxy resin fabricated by CAD/CAM and showed that these materials have attractive optical properties and excellent adaptation in the root canal. More recently, some reports have indicated that customized post and cores milled from fiberglass blocks are practical and efficient clinical alternatives.[17]

Different resinous materials can be used for luting fiberglass posts, such as self-adhesive resin cements or resin cements requiring an adhesive system.[18] Post retention depends on the adhesion between the post and resin cement as well as between the resin cement and root dentin. There is little scientific evidence regarding the bond strength of a CAD/CAM fiberglass post to root dentin using different resin cements.[19-21]

Therefore, this study aimed to evaluate the pull-out force of a prefabricated fiberglass post (PP), relined fiberglass post (RP), or milled fiberglass post (MP) luted with Multilink N (MN), RelyX Unicem 2 (RXU2), or RelyX Ultimate (RU) to enlarged root canals. Additionally, the thickness of the resin cements and the presence of gaps and bubbles (voids) in the resin cement film were analyzed by microcomputed tomography (μCT). The hypotheses of the study were that 1) the post type and 2) resin cement influence the pull-out force to root dentin and that the fiberglass post type influences the 3) resin cement thickness and 4) void formation.

METHODS AND MATERIALS

Experimental Design

Ninety permanent bovine incisors with similar root sizes, lengths, and open apexes were selected. The teeth were cleaned and stored in distilled water at 4°C. The crowns were removed with a low-speed diamond disc under cooling below the cementoenamel junction. A small mark was made on the cervical buccal surface of the root with a spherical diamond bur in order to locate this face in the cyclic mechanical loading test. The length of the roots was standardized to

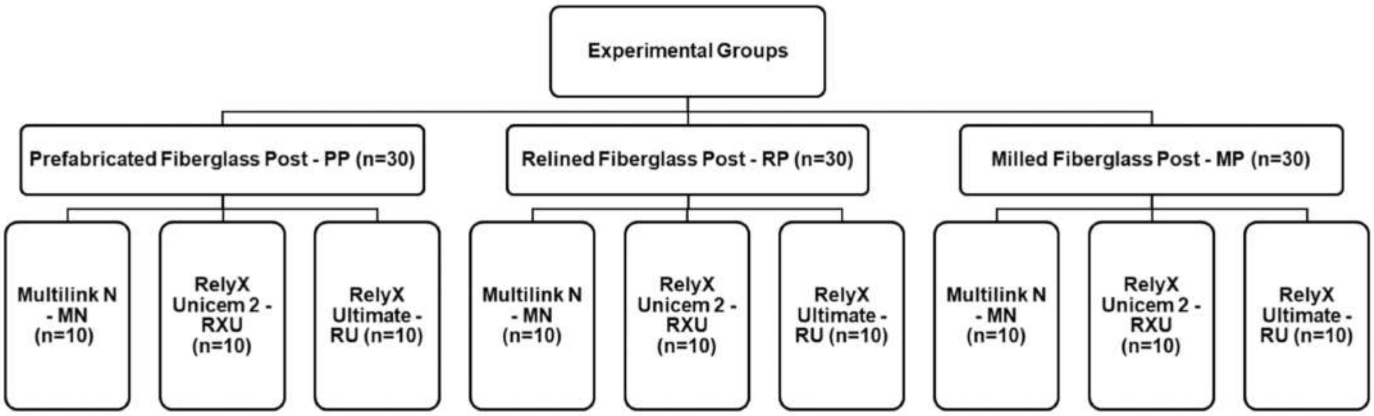

Figure 1. *Division of the groups in the study.*

16 mm. The canals were emptied, and the teeth were disinfected with 1% chloramine-T for seven days and then remained in distilled water.

The specimens were randomly divided into nine groups (n=10) according to the fiberglass post type—prefabricated fiberglass post #5 Exacto (PP), relined fiberglass post (RP), milled fiberglass post (MP), and resin cement—Multilink N (MN), RelyX Unicem 2 (RXU2), and RelyX Ultimate (RU), as shown in Figures 1 and 2. The materials used in this study are presented in Table 1.

Endodontic Treatment

A step-back preparation technique was performed for the endodontic treatment with stainless-steel #60 to #80 K-files and Gates Glidden #4 and #5 drills. All the enlargement procedures were followed by irrigation with a 2.5% sodium hypochlorite solution. A final irrigation with 17% EDTA was carried out for 5 min followed by washing with distilled water. The prepared root canals were filled with gutta-percha cones using lateral condensation and AH Plus resin sealer (Dentsply, Konstnaz, Germany). Then, the teeth were stored in 100% humidity at 37°C for seven days.

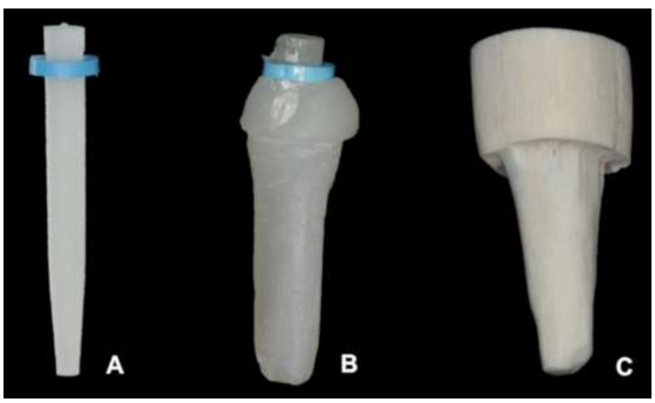

Figure 2. *Representation of post types: A - prefabricated fiberglass post (PP), B - relined fiberglass post (RP), and C - milled fiberglass post (MP).*

The gutta-percha was removed with a heated Rhein instrument (Golgran, São Caetano do Sul, SP, Brazil) until it reached 10 mm. The root canals were enlarged with a Largo #5 drill and high-speed diamond burs #4138 and #4137 (KG Sorensen, Cotia, SP, Brazil) with water irrigation. The remaining cervical dentin wall was approximately 1.0 mm thick, as measured with a digital caliper.

Post Preparation

Relined post (RP)—Exacto #5 posts (Angelus, Londrina PR, Brazil) were cleaned with 70% alcohol and gently air-dried. A layer of silane was applied to the surface of the posts for 1 minute and air-dried. A layer of Adper Single Bond 2 (3M ESPE, St Paul, MN, USA) was applied to the post surface, and the adhesive was air-dried. The tip of a Radii Cal curing light (SDI, Bayswater, Vic, Australia) was positioned in the apical portion of the post and the adhesive was light-cured for 10 seconds with a light intensity of 1000 mW/cm^2 as assessed by a radiometer (Model 100 Demetron, Saint Louis, MN, USA). A nanohybrid resin composite (A2D, Filtek Z350 XT, 3M ESPE, St. Paul, MN, USA) was used to customize the post. The composite resin was placed on the surface of the post and inserted into the root canal previously isolated with a water-soluble gel (KY Gel, Johnson & Johnson, São José dos Campos, SP, Brazil). The RP was light-cured for 20 seconds into the root canal. The RP was removed from the root canal, the tip of the light-curing unit was positioned in the apical portion of the post and the composite resin was light-cured for an additional 20 seconds. KY Gel was rinsed for 30 seconds after the relining procedure.

Milled post (MP)—The root canal was covered with CEREC Optispray (Cerec Optispray, Sirona, Bensheim,

Table 1: *Materials, Composition, Batch Number, and Manufacturer*[a]

Material/ Manufacturer	Composition	Batch
Exacto #5	Conical fiberglass post with 80% of glass fiber and 20% of epoxy resin	41799 100493
Fiber Cad	Glass fiber (75-80%) and epoxy resin (20-25%) block for CAD/CAM system	45769 45770
Multilink N	Primer A: 2,2'-[(4- methylphenyl)imino]bisethanol Primer B: HEMA, phosphoric acid acrylate Base: Ytterbium trifluoride, ethyoxylated bisphenol Adimethacrylate, Bis-GMA, 2-HEMA, 2-dimethylaminoethyl methacrylate Catalyst: Ytterbium trifluoride, ethyoxylated bisphenol-A dimethacrylate, urethane dimethacrylate, 2-HEMA,dibenzoyl peroxide	W11558 X36488 X29757
RelyX Unicem 2	Base paste: glass powder treated with silane, 2-propenoic acid, 2-methyl 1,10-(1- [hydroxymetil]-1,2- ethanodlyl) ester dimethacrylate, TEGDMA, silica-treated silane, glass fiber, sodium persulfate and per-3,5,5-trimethyl hexanoate t-butyl; Catalyst paste: glass powder treated with silane, substitute dimethacrylate, silica treated silane, sodium p-toluenesulfonate, 1- benzyl-5-phenyl-acid barium, calcium, 1,12- dodecane dimethacrylate, calcium hydroxide, and titanium dioxide	1811500433 1805800425
RelyX Ultimate	Base paste: Silane--treated glass powder, 2-propenoic acid, 2-methyl-, reaction products with 2-hydroxy-1,3-propanedyl dimethacrylate and phosphorus oxide, TEGDMA, silane--treated silica, oxide glass chemicals, sodium persulfate, tertbutyl peroxy-3,5,5- trimethylhexanoate, copper acetate monohydrate Catalyst paste: Silane-treated glass powder, substituted dimethacrylate, 1,12-dodecane dimethacrylate, silane--treated silica, 1-benzyl-5-phentyl-barbic-acid, calcium salt, sodium p-toluenesulfinate, 2-propenic acid, 2-methyl-, di-2,1-ethanediyl ester, calcium hydroxide, titanium dioxide	1808500058 3472648
Scotchbond Universal	BisGMA, HEMA, decamethylene dimethacrylate, ethanol, water, silane-treated silica, 2-propenoic acid, methacrylated phosphoric acid, copolymer of acrylic and itaconic acid, ethyl-4- dimethylaminobenzoat, camphorquinone, (dimethylamino) ethyl methacrylate, methyl ethyl ketone	3296401
RelyX Ceramic Primer	Ethanol, water, 3-methacryloxypropyltrimethoxysilane	N878550
Monobond-S	Ethanol, water, 3-methacryloxypropyltrimethoxysilane	X21804
Filtek Z350 XT	Bis-GMA, UDMA, TEGDMA, Bis-EMA, zirconia and silica nanoparticles (78.5 wt%/ 59.5 vol%)	896960
Adper Single Bond 2	BisGMA, HEMA, UDMA, dimethacrylates, ethanol, water, camphorquinone, photoinitiators, polyalkenoic acid copolymer, 5-nm silica particles	N688653

Abbreviations: HEMA, hydroxyethyl methacrylate; BisGMA, bisphenol A-glycidyl methacrylate; TEGDMA, triethylene glycol dimethacrylate; Bis-EMA, ethoxylated bisphenol-A dimethacrylate; UDMA, urethane dimethacrylate.
[a] *The chemical composition information was obtained from the manufacturer's material safety data sheet.*

Germany) and scanned with CEREC Omnicam (Sirona, Bensheim, Germany). The root canal was rinsed with distilled water with the aid of a syringe for 30 seconds to remove the Optispray. The digital 3D model was created and designed with Cerec 4.6 software (Sirona, Bensheim, Germany). The fit of the post was planned at 100 μm. The block of Fiber CAD was milled in an inLab MC XL machine (Sirona, Bensheim, Germany).

Table 2: *Bonding Procedures Applied in the Experimental Groups*

Resin Cements/ Activation Mode	Dentin Pre-treatment	Post and Relined Post Treatment (PP, RP, MP)
Multilink N (MN) Self-cure	Multilink N Primers A and B were mixed at a 1:1 ratio and applied to the root canal with a microbrush, agitated for 30 s, and air-dried for 5 s. Excess material was removed with paper points.	A layer of Monobond-S was applied to the post surfaces with a microbush, left undisturbed for 60 s, and gently air-dried for 5 s.
RelyX Unicem 2 (RXU2) Dual-cure	No treatment, only a rinse with water, and excess water was removed from the root canal with absorbent paper points.	RelyX ceramic primer was applied to the post surface with a microbrush, left undisturbed for 60 s, and gently air-dried for 5 s.
RelyX Ultimate (RU) Dual-cure	Scotchbond Universal was applied into the root canal with a microbrush, agitated for 20 s, and gently air-dried for 5 s.	Scotchbond Universal was applied to the post surfaces with a microbrush, agitated for 20 s, and gently air-dried for 5 s.

Bonding Procedures

The bonding procedures applied in the experimental groups are described in Table 2. The mixing procedure of all the resin cements was standardized. Equal quantities of base and catalyst pastes of the resin cements were hand-mixed for 20 seconds and inserted into the canal using a Centrix syringe (NOVA DFL; Rio de Janeiro, RJ, Brazil) with AccuDose Tips. The RXU2 and RU resin cements were light-cured for 40 seconds according to the manufacturer's instructions, except MN, which was applied as a self-cured resin cement.

Micro-CT Images

After the bonding procedures, the samples were stored at 100% relative humidity at 37°C for 24 hours. The samples were scanned using a micro-CT (μCT) scanner (model 1173; Skyscan, Kontich, Belgium). The μCT was calibrated to operate under conditions of 85 kV and 65 μA, with an image pixel size of 9 μm, a rotational step of 0.22°, and an 800-ms exposure time. The average number of slices per specimen was 2150. For each specimen, 655 to 677 TIFF images were obtained. The obtained images were reconstructed using NRecon (Skyscan, Kontich, Belgium) software as demonstrated in Figure 3.

Resin Cement Thickness and Void Formation

The resin cement thickness was measured using Data Viewer software (Skyscan, Kontich, Belgium). The images were analyzed in a sagittal view (Z-Y). The coronal view (X-Z) and transaxial view (X-Y) were centralized at the center of the fiberglass post. Twenty equidistant measurements of the thickness of the resin cement film between the canal wall and the post were taken, as shown in Figure 4.

The images were also analyzed for the presence of voids and classified according to the extension and number of voids using the following scores: 0 = almost imperceptible voids; 1 = few and small voids in the resin cement film; 2 = many and small voids in the resin cement film; 3 = few and large voids in the resin cement film; and 4 = many and large voids in the resin cement film.

Cyclic Mechanical Loading and Pull-Out Testing

The roots were embedded with a self-cured acrylic resin (Jet Clássico, São Paulo, SP, Brazil) in a PVC cylinder that was 15 mm high and 25 mm in diameter. Regardless of the different shapes and sizes of the

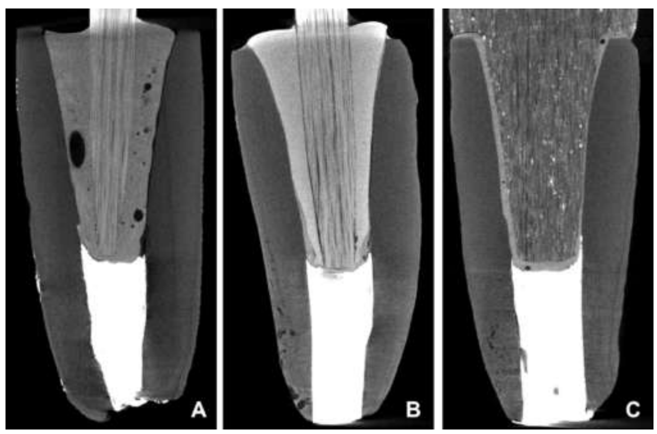

Figure 3. *Micro-CT images of fiberglass post types luted in the root canal: (A) prefabricated fiberglass post (PP); (B) relined fiberglass post (RP); and (C) milled fiberglass post (MP).*

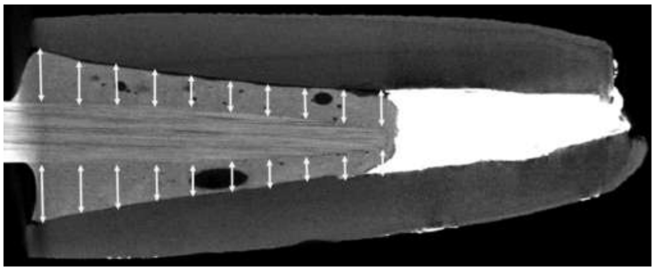

Figure 4. *Measurements of the resin cement thickness of a luted fiberglass post.*

coronal portions of the posts, it was necessary to apply composite resin on the facial face of the coronal portion of the post in order to serve as a niche for the plunger of the mechanical cycling machine. The samples were then submitted to cyclic mechanical loading (ER-11000, Erios, São Paulo, SP, Brazil) at 50 N using 500,000 cycles at 1 Hz in distilled water. The load was applied to the niche of composite resin at an angle of 45°.[22] After cycling mechanical loading, the samples were submitted to the pull-out force test.

The pull-out test was performed at a crosshead speed of 1.0 mm/min using a universal testing machine (EMIC, São José dos Campos, PR, Brazil) with a 1000-N load cell. The maximum load causing dislodgement of the post from the root canal wall was recorded in newtons (N). The mode of failure was assessed at 45× magnification under a stereomicroscope (SZH10, Olympus Corp., Tokyo, Japan) and was classified as follows: (a) adhesive failure at the dentin-resin cement interface; (b) adhesive failure at the post or relined post-resin cement interface; (c) mixed (combination of the failures "a" and "b" — resin cement covering parts of the post surface and parts of the dentin surface); (d) cohesive failure at the dentin; (e) cohesive failure at the post or relined post; and (f) adhesive failure at the post and relining composite resin interface.

Statistical Analysis

Two-way ANOVA (fiberglass post x resin cement) followed by Tukey's test was used to analyze the pull-out force data and resin cement thickness data. Pearson's correlation test was used to identify any correlation between the pull-out force and resin cement thickness. The void scores were analyzed by Kruskal-Wallis followed by Bonferroni tests. Statistical significance was set at 0.05. SPSS statistics 17 (IBM, ON, Canada) was used to carry out the statistical analyses.

RESULTS

According to two-way ANOVA, the fiberglass post factor ($p<0.001$), the resin cement factor ($p<0.001$), and the interaction between the factors ($p<0.001$) were significant for the pull-out force.

Comparing the posts for each resin cement, luting with MN provided a significantly higher pull-out force for RP (703±153 N). PP (344±142 N) and MP (404±136 N) did not differ significantly from each other. Luting with RXU2 promoted a significantly higher pull-out force for MP (510±124 N). PP (221±81 N) and RP (310±94 N) did not differ significantly from each other. For RU, the three types of posts differed significantly from each other, and RP (839±175 N) achieved the highest pull-out force, followed by MP (605±183 N) and PP (391±86 N) (Table 3).

Comparing the resin cements for each post, the pull-out forces of PP luted with RU (391±86 N) and MN (344±142 N) did not differ significantly and were significantly higher than that of RXU2 (221±81 N). The pull-out forces of RP luted with RU (839±175 N) and MN (703±153 N) did not differ significantly and were significantly higher than that of RXU2 (310±94 N). Higher pull-out forces were obtained for MP luted with RU (605±183 N) and RXU2 (510±124 N), which did not differ statistically from each other. The pull-out force of MP luted with RXU2 (510±124 N) did not differ significantly from MN (404±136 N) (Table 3).

Different modes of failure occurred in the groups (Table 4). Higher percentages of adhesive failure at the dentin-resin cement interface occurred for PP, RP, and MP luted with RXU2. For RP and MP luted with MN there was a predominance of adhesive failure at

Table 3: *Pull-out Force (N) and Standard Deviation of the Posts Luted to Root Dentin with the Resin Cements*[a]

	Prefabricated Fiberglass Post (PP)	Relined Fiberglass Post (RP)	Milled Fiberglass Post (MP)
Multilink N (MN)	344 ± 142 Ba	703 ± 153 Aa	404 ± 136 Bb
RelyX Unicem 2 (RXU2)	221 ± 81 Bb	310 ± 94 Bb	510 ± 124 Aab
RelyX Ultimate (RU)	391 ± 86 Ca	839 ± 175 Aa	605 ± 183 Ba

[a] *Mean values with different uppercase letters (rows) and different lowercase letters (columns) indicate significant differences according to Tukey's test (p<0.05).*

Table 4: *Mode of Failures (%) Observed for each Group*[a]

Mode of Failures	Adhesive at the Dentin-Resin Cement Interface	Adhesive at the Post or Relined Post-resin Cement Interface	Mixed	Cohesive at Dentin	Cohesive at Post or Relined Post	Adhesive at the Post and Relining Composite Resin Interface
MN + PP	1 (10%)	6 (60%)	3 (30%)	—	—	—
MN + RP	5 (50%)	3 (30%)	1 (10%)	1 (10%)	—	—
MN + MP	5 (50%)	—	5 (50%)	—	—	—
RXU2 + PP	7 (70%)	1 (10%)	2 (20%)	—	—	—
RXU2 + RP	10 (100%)	—	—	—	—	—
RXU2 + MP	10 (100%)	—	—	—	—	—
RU + PP	4 (40%)	2 (20%)	4 (40%)	—	—	—
RU+ RP	3 (30%)	4 (40%)	—	—	3 (30%)	—
RU + MP	—	2 (20%)	4 (40%)	4 (40%)	—	—

Abbreviations: MN, Multilink N; PP, prefabricated fiberglass post; RP, relined fiberglass post; MP, milled fiberglass post; RXU2, RelyX Unicem 2; RU, RelyX Ultimate
[a] *"—" indicates no failure.*

the dentin-resin cement interface. Most failures were adhesive at the post-resin cement interface for PP luted with MN. There was greater variability in the occurrence of the different failures for the samples luted with RU. Figure 5 shows the failures.

According to two-way ANOVA, the resin cement factor (p=0.481) and interaction between factors (p=0.743) were not significant for resin cement thickness. However, the fiberglass post factor (p<0.001) was significant. The three fiberglass posts showed significant differences. PP provided a higher resin cement thickness (1054±56 μm), followed by MP (301±19 μm) and RP (194±47 μm).

Pearson's correlation indicated an inverse relationship between the resin cement thickness and pull-out force (r^2=0.99; p<0.05) for all the resin cements (Figure 6).

According to the Kruskal-Wallis test, the resin cement factor was not significant (p=0.941) and the post factor was significant (p<0.001) for void formation. The Bonferroni test indicated that all the posts differed significantly from each other for extension and void quantity (Figure 7). Scores 2 and 3 were observed for PP, scores 1 and 2 for MP, and scores 0 and 1 for RP.

DISCUSSION

In the present study, all groups were considered experimental, without a control group, since various luting agents and corresponding adhesive systems have been proposed for bonding different types of fiberglass posts to root canal. The materials were selected because of the distinct etching methods and modes of polymerization.

The results showed that the pull-out force was significantly influenced by the post type and resin

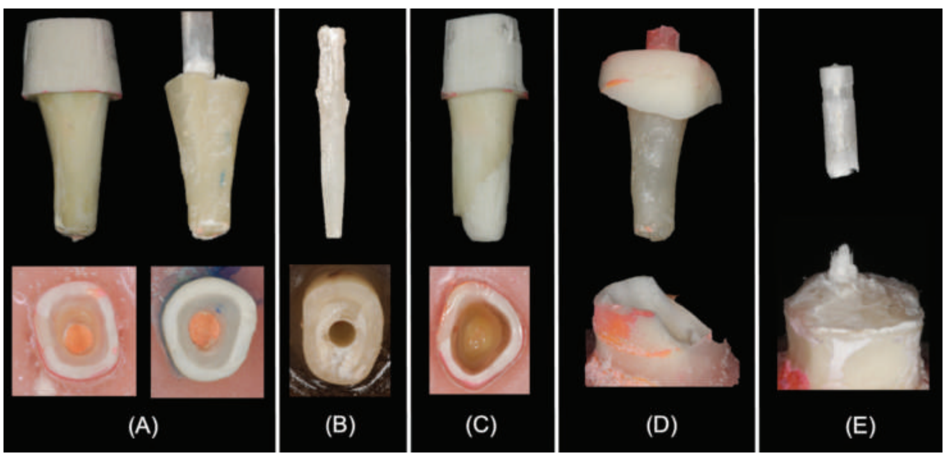

Figure 5. *Mode of failures: (A) adhesive at the dentin-resin cement interface; (B) adhesive at the post-resin cement interface; (C) combine or mixed; (D) cohesive at dentin; and (E) cohesive at post.*

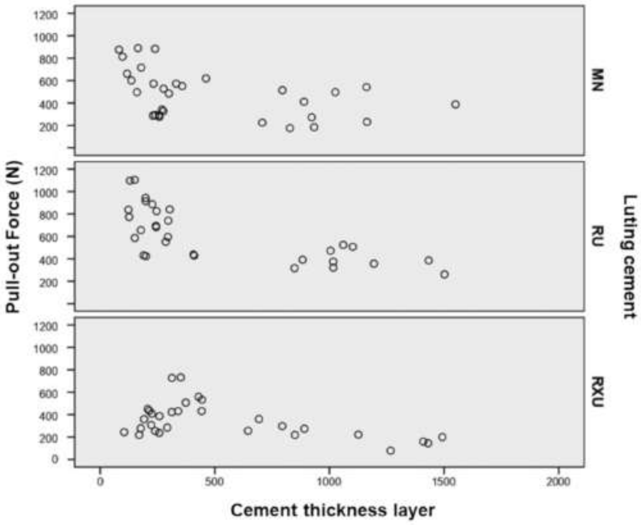

Figure 6. *Pearson's correlation between resin cement thickness and pull-out force.*

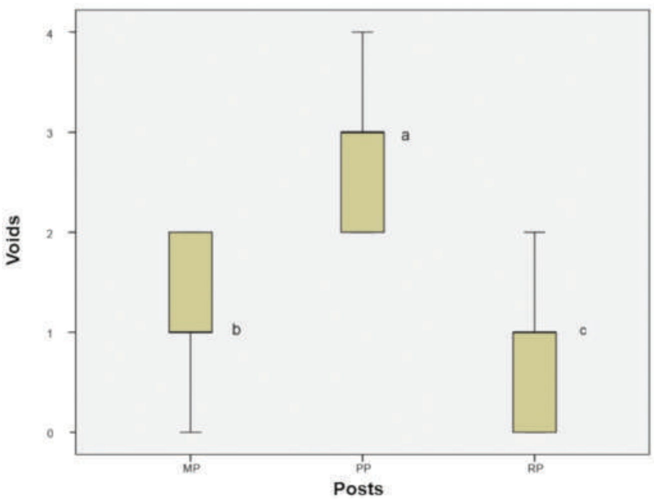

Figure 7. *Effect of fiberglass posts on the formation of voids in the resin cement. Different letters indicate differences according to Bonferroni's test (*$p<0.05$*).*

cement, leading to the acceptance of the first two hypotheses. PP luted with RU and MN showed a higher pull-out force than RXU2. RU requires the application of a universal adhesive, which was used in the self-etching technique in the present study. MN requires a self-etch primer prior to the application of resin cement. These approaches partially demineralize dentin, leaving a substantial amount of hydroxyapatite crystals around the collagen fibrils, providing mechanical retention through the formation of a hybrid layer and chemical bonding with specific carboxylic or phosphate groups of functional monomers.[23,24] In addition, the Scotchbond Universal adhesive system, previously applied to RU, contains the monomer 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP), which allows a chemical bond to form between phosphate groups and residual hydroxyapatite crystals on the dentin collagen scaffold. This chemical bond reduces degradation of the hybrid layer over time and is more stable in water than the chemical bond obtained with other functional monomers.[23,25]

Beyond the pull-out force evaluation, it is also important to evaluate the mode of failures, as they represent the least resistant area to the stresses that occur during the pull-out test. Adhesive failures between PP and resin cement occurred in 20% of the RU specimens and 60% of the MN specimens. This mode of failure suggests that the pull-out force between the PP and resin cement was lower than that between the root dentin and adhesive material. In this study, the PP surface treatment followed the manufacturer's instructions. For luting with MN, the PP was treated with silane (Monobond S); for luting with RU, Scotchbond Universal adhesive system was applied on PP. It is possible that these failures would have been diminished if the post had been etched with hydrogen peroxide or sandblasted with aluminum oxide particles. These procedures enhance the surface roughness of the fiberglass post, exposing more glass fibers and increasing the bond strength to the adhesive agent.[26,27] There were also 40% mixed failures for RU and 30% for MN. This failure is characterized by the cohesive fracture of the resin cement itself, showing that the bond of the resin cement to the root dentin has overcome the cohesive strength of the material. Therefore, it is estimated that the pull-out force of RU and MN to the root dentin, which corresponds to adhesive failure between the substrate and resinous material (40% for RU and 10% for MN), could be higher if mixed or adhesive failure between the PP and resin cement had not occurred.

The luting of PP with RXU2 provided a lower pull-out force. RXU2 is a self-adhesive resin cement that presents methacrylate monomers containing phosphoric acid groups, which provide dentin conditioning. These monomers simultaneously demineralize hydroxyapatite and infiltrate the superficial dentin, providing micromechanical retention and chemical bonding that occurs from an acid-base reaction between the acid monomers and the dental substrate or acid-soluble inorganic fillers.[18,28,29] The low pull-out force obtained with RXU2 could be attributed to the low diffusion of the resin cement in the demineralized dentin and the absence of a hybrid layer or resin tags.[18,30] Although the PP surface was treated with silane alone for luting with RXU2, there was only 10% adhesive failure between the PP and resin cement, and most of the failures were adhesive between the dentin and resinous material

(70%). This result corroborates the lower pull-out force obtained with RXU2.

PP and RP luted with RU and MN obtained a greater pull-out force than RXU2. However, the pull-out force of RP was significantly higher than that of PP, and the Pearson's correlation test indicated an inverse relationship between the resin cement thickness and pull-out force. This finding is related to the significantly thinner resin cement layer obtained for RP than PP. Thus, the third hypothesis was accepted. This result was expected since PP does not fit the weakened root and the space between the post and the root walls is filled with resin cement. In contrast, RP is modeled with composite resin inside the root canal, allowing better adaptation to the root canal walls. The thin space between the root dentin and RP is filled with resin cement. Previous studies have demonstrated that the proximity between the root canal walls and RP increases the sliding friction[31] and improves post retention,[11] promoting a higher pull-out force.[8,13,32] In addition, RP pushes the resin cement against the root canal walls during the luting procedure, favoring tag formation into the dentinal tubules. These resin tags could favor an increase in pull-out force.[12] The poor adaptation between PP and the dentin root walls results in a thick resin cement layer that may lead to higher polymerization shrinkage and air entrapment, weakening the bond and increasing the possibility of post debonding.[7,8,33]

In RP, adhesive failure between the relined post and resin cement occurred in 40% of the RU specimens and 30% of the MN specimens. This failure took place between the composite resin used for the relining and the resin cement. This finding also demonstrates that a higher pull-out force could be obtained if another type of surface treatment of the composite resin covering the post had been carried out, such as air abrasion with alumina particles.[34] In the present study, the surface treatment of the relining composite resin followed the procedures used for PP and MP with the aim of standardization for each resin cement. However, there were 100% adhesive failures between the dentin and resin cement for RXU2, providing a lower pull-out force. The present study does not corroborate the result of other studies in which the use of this self-adhesive resin cement promoted a higher bond strength to the root dentin compared with resin cements requiring an adhesive.[22,35] One possible explanation for the different results is the methodology applied in the studies since most of them evaluated the bond strength through the push-out bond test and not the pull-out force test.[36]

Regarding the failures obtained in the RP group, there was no adhesive failure at the relining composite resin and fiberglass post. This result shows an adequate bond between the relining composite resin and fiberglass post, which was obtained by the application of silane and adhesive. An important step involving the RP technique is the KY gel application in the root canal to avoid the bond between the relining composite resin and root dentin. As this gel is water-soluble and was abundantly rinsed after the relining procedure, it is not expected it had any influence on the bonding of RP in the root canal.

MP presented an intermediate resin cement thickness (301 μm) compared with PP (1054 μm) and RP (194 μm). The milling spacer was set to 100 μm, which is very close to the cast post and core found in the study of Tsintsadze and others.[20] However, when analyzing the luting film along the root canal by microCT images, it was observed that it varies. These findings agree with the study of Prudente and others,[37] which showed a resin cement film ranging from 16 to 230 μm with a milling space of 70 μm. This finding can be explained by software compensation because of anatomical details, imperfections related to the preparation, and difficulties in the capture and construction of the image, increasing the misfit of the post.[38]

MP luted with RU showed a significantly greater pull-out force, not differing significantly from RXU2. Thus, the lowest pull-out force was obtained with MN, which did not differ significantly from RXU2. Although luting with RXU2 promoted an intermediate pull-out force for MP, 100% adhesive failures occurred between the resin cement and root dentin. This finding demonstrates the same tendency for adhesive failure that occurred for the PP and RP luted with RXU2. Thus, the pull-out force of this resin cement to root dentin did not exceed the bond strength between the post and the resin cement and did not overcome the cohesive strength of the resin cement itself. MP luted with RU resulted in 20% adhesive failures between the post and the resin cement. MP was only treated with the Scotchbond Universal adhesive for luting with RU. It is possible that an additional chemical or micromechanical surface treatment could increase the bond strength between the adhesive and the post, preventing this type of failure.[21] There were also 40% mixed failures and 40% dentin failures, showing strong bonding of the adhesive material to the root dentin. It is estimated that the pull-out force obtained for MP luted with RU exceeded the cohesive strength of dentin itself. For MN, 50% of adhesive failures occurred between dentin and the resin cement, and 50% were mixed failures. Therefore, it is also estimated that in 50% of the specimens, the pull-out force exceeded the cohesive strength of the resin cement itself. Thus, the resin cements requiring adhesive demonstrated a greater capacity to promote retention of the posts inside the root canal.

The insertion of resin cement into the root canal and void formation influences the bond quality between the dentin walls and posts.[39,40] Void formation is mainly a result of air entrapment in the resin cement during the mixing process. Automatically mixed resin cement insertion reduces void formation in the material because the base paste and catalyst paste are not in contact with air during mixing. This reduction in void formation favors an increase in the bond strength of the resin cement to the substrate.[39-41] However, in this study, for standardization purposes, all the resin cements were hand-mixed and inserted into the root canal using a Centrix syringe. Silva and others showed that a Centrix syringe reduced apical void formation in comparison with hand-mixed resin cements and insertion using endodontic files. Additionally, the Centrix syringe allows a homogeneous resin cement interface.[39] Micro-CT analysis showed a certain number of voids inside all the tested groups, which was influenced by the fiberglass post type. Thus, the fourth hypothesis was accepted. PP presented many small voids and few large voids in the resin cement film. For RP, the voids were almost imperceptible, or there were a few small voids. For MP, there were either few or many small voids. These findings agree with previous studies.[8,41,42] These results may indicate that the post customization, obtained by RP and MP, minimizes the resin cement thickness layer[12,42] and void formation,[42,43] increasing the bond strength and enhancing the survival time of the post.[41]

Post retention has been evaluated by push-out and pull-out tests.[36] Post retention depends not only on chemical bonds provided by the luting agent but also on micromechanical interlocking and sliding friction.[31] Since one of the most common failures involving fiberglass posts is debonding,[9,10] the pull-out test was chosen for this study. The pull-out test allows a simultaneous evaluation of the shear and tensile stresses that develop during the test,[44-47] resulting in the force necessary for debonding the post surface in the entire length of the root canal, not only in root segments, such as in the push-out test. These characteristics of the pull-out test allow greater clinical relevance of the results.

It is important to emphasize that the pull-out force values may also have been influenced by the different modes of polymerization. Dual resin cements, such as RU and RXU2, are light-cured and chemically cured. These materials have been recommended to lute fiberglass posts, because the curing light is not able to ensure adequate polymerization in deep areas of the root canal.[48] However, the self-cured reaction of dual resin cements is not capable of totally compensating for poor polymerization in deep areas where light intensity is low, favoring a lower degree of conversion[49] and lower bond strength value in the apical third.[18,49] In contrast, self-cured resin cements, such as MN, are activated by the peroxide-amine system without requiring light exposure; hence, the polymerization is not influenced by root canal depth.[50]

Cyclic mechanical loading is a laboratory aging methodology that aims to submit the specimens to a cyclic load to reproduce the masticatory loads that are applied to the teeth. In the present study, the samples were submitted to 500,000 cycles with a 50 N load. In this way, approximately two years of normal functionality was simulated.[51,52] The load was applied to the post head that varied in shape among the posts, being larger for MP. It is possible that the force transmitted down the canal was different among the posts. Therefore, it cannot be ruled out that the different post heads have influenced the results of the pull-out force.

The results of the present study demonstrated that both RP and MP presented better performance in enlarged roots than PP. However, it is important to highlight that RP has numerous adhesive interfaces, increasing the chance of material degradation at the interfaces and, consequently, bond failures.[14,53] In contrast, MP is manufactured as a single piece without interfaces. A homogeneous fiberglass block is submitted to a controlled milling process and with a fully digital workflow.[16,19,42] Due to the lack of literature on MP, further studies should be conducted to evaluate the pull-out force of these posts to the root dentin under long-term conditions. In addition, studies related to the pretreatment of MP should be carried out.

CONCLUSIONS

Within the limitations of this laboratory study, the following conclusions can be drawn:

1. Post customization, such as relined or milled fiberglass posts, decreased resin cement thickness and void formation and favored a higher pull-out force to enlarged roots compared to prefabricated fiberglass posts.
2. Resin cements requiring adhesive application (Multilink N and RelyX Ultimate) favored a higher pull-out force than self-adhesive resin cement (RelyX Unicem 2).

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Conflict of Interest

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

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