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Internal Fit and Bond Strength of Customised CAD/CAM 3D-Printed and Milled Resin-Based Posts vs Relined Fibre Posts

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ABSTRACT

Objective: This study assessed the internal adaptation and push-out bond strength (PBS) of customised CAD/CAM 3D-printed (Varseosmile Crown Plus, Bego, Germany - 3DP) and milled (Enamic, Vita, Germany - MP) resin-based posts vs prefabricated fiber posts relined with resin composite (RelyX fiber post and Filtek Bulkfil Composite, 3M Health Care, USA - RFP).

Materials and Methods: Twenty-four premolars were decoronated, root canal treated, then divided into three groups: 3DP, MP, and RFP (control group). Impressions of the prepared teeth in the 3DP and MP groups were taken using light-body polyvinyl siloxane, then 3D scanned for CAD/CAM design and fabrication. In the RFP group, fibre posts were relined with resin composite and adapted to the post space. Cement gaps were evaluated at the coronal, middle, and apical thirds using micro-computed tomography. All posts were cemented with self-adhesive resin cement, and PBS was tested at the three root thirds using a universal testing machine. Data were analysed using Two-way ANOVA and Bonferroni post-hoc tests ($P = .05$).

Results: RFP exhibited the least cement space, with statistically higher internal adaptation compared to 3DP and MP ($P < .001$). However, no significant differences were found in PBS among the 3 tested fabrication techniques ($P > .05$). The root section had no statistically significant effect on internal adaptation ($P > .05$) but significantly affected PBS ($P < .05$). The poorest adaptation and the lowest PBS were found in the apical section.

Conclusion: 3D printing of resin-based posts demonstrates the potential to fabricate anatomically customised CAD/CAM posts with clinically acceptable internal adaptation and bond strength comparable to milled and relined counterparts. These findings support its application in flared or non-circular canals, though further evaluation of fatigue and fracture resistance is required to establish clinical durability.

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Introduction

Traditionally, cast metal posts have been regarded as the gold standard for restoring severely compromised endodontically treated teeth (ETT), however, their high rigidity and wedging effect increase the risk of root fracture.[1] Furthermore, their susceptibility to corrosion, prolonged fabrication time, and poor aesthetic outcomes, particularly in anterior teeth, limit their clinical efficiency and make them less suitable for visible restorations.[2,3] To address these limitations, fibre posts have been introduced as an alternative, offering better flexibility, improved stress distribution, and a more aesthetic outcome.[4] Despite these biomechanical and aesthetic advantages, the clinical efficacy of prefabricated fibre posts is often challenged by the anatomical shape of canals, as the standardised cylindrical or tapered shapes of these posts frequently fail to conform to flared, ovoid, or irregularly shaped root canals, resulting in an excessively thick and uneven cement layer.[5] This poor adaptation can create voids, compromise bond strength, and ultimately jeopardise the longevity of the restoration.[6]

To improve adaptation and bonding relined fibre posts have been proposed, a technique that involves modifying a prefabricated fibre post by adding composite resin to achieve a better fit within the canal space.[7] Studies suggested that relined fibre posts can enhance internal adaptation, reduce cement thickness, and improve stress distribution, potentially increasing the longevity of the restoration.[8-10] On the other hand, an alternative approach was introduced through CAD/CAM-fabricated customised posts, where various materials and fabrication methods have been explored, including subtractive manufacturing (milling) and additive manufacturing (3D printing).[11-13] CAD/CAM-milled posts provide better retention and reduce cement thickness compared to prefabricated posts.[14] Additionally, additive manufacturing has gained traction in prosthodontics due to its ability to reduce costs, enhance customisation, and minimise material waste.[15] 3D-printed resin posts exhibited similar accuracy to that of the milled and directly fabricated posts, and the fracture resistance of the 3D-printed custom-made resin posts was found to be as effective as fibreglass posts.[16,17] The commercially available CAD/CAM milled and 3D-printed resin-based materials have fundamentally different mechanical properties (eg, flexure strength, elastic modulus, fracture toughness), which could independently influence both adaptation (due to different machining/printing shrinkage and stability), and more critically, the bond strength results.[18,19]

Up to the time of this manuscript submission, no studies have investigated the internal adaptation of the 3D-printed permanent resin posts, and only one article reported comparable push-out bond strength to glass fibre posts.[20] Given that internal adaptation is a critical factor influencing post and core retention, bonding strength, and long-term clinical success, this knowledge gap needs to be addressed. Thus, this study aimed to evaluate the internal adaptation and push-out bond strength (PBS) of CAD/CAM 3D-printed and milled permanent resin-based posts in comparison to relined fibre posts. The null hypothesis stated that no significant differences would exist in internal adaptation or push-out bond strength among the three fabrication techniques tested or across the different root levels.

Materials and methods

The materials used in this study are listed in Table 1.

Table 1 – Materials used in the study.

Material	Type	Manufacturer	Composition	Lot
Varseosmile Crown Plus	3D-printed resin composite	Bego, Breman, Germany	4.4′-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, 30%–50% by mass inorganic filler (particle size 0.7 μm), silanised dental glass, methyl benzoyl formate, diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide	600671
Enamic	CAD/CAM milled Polymer-Infiltrated Ceramic Network (PICN)	Vita Zahnfabrik, Bad Sackingen, Germany	Bis-GMA, UDMA, Bis-EMA, TEGDMA, SiO2 (20 nm), ZrO2 (4–11 nm), 86wt% aggregated ZrO2/SiO2 cluster (SiO2 = 20 nm, ZrO2 = 4–11 nm)	38630
RelyX fibre post	Glass fibre-reinforced post	3M Health Care, St Paul, MN, USA	60%–70% Glass fiber, epoxy resin, zirconia filler	358961809
Filtek Bulk Fill Flowable	Flowable bulk fill composite	3M Health Care, St Paul, MN, USA	Monomers: BisGMA, BisEMA, Procrylat, UDMA Fillers: zirconia/silica and YbF3 (64.5 wt% / 42.5 vol%), photoinitiator: camphoroquinone	NC97453
Rely X Unicem2 Automix	Dual-cure self-adhesive Resin cement	3M Health Care, St Paul, MN, USA	**Base:** TEGDMA (30%–50% weight) Methacrylates with phosphoric acid groups. Total filler content: ∼70 % weight. Filler particle size: 90 %∼12.5 μm **Catalyst:** (Substituted) dimethacrylates (20–30 % weight)	10007419
IPS Ceramic Etching Gel,	Hydrofluoric acid	Ivoclar Vivadent, Schaan, Liechtenstein	4.8% hydrofluoric acid	U01182
Monobond-Plus	Universal ceramic primer	Ivoclar Vivadent, Schaan, Liechtenstein	Ethanol, 3-trimethoxysilylpropyl methacrylate, 10-MDP, disulfide acrylate	U25466

*BisGMA, Bisphenol A polyethylene glycol diether dimethacrylate; BisEMA, Bisphenol A polyethylene glycol diether dimethacrylate; UDMA, Urethane dimethacrylate; TEGDMA, Triethylene glycol dimethacrylate; YbF3, ytterbium trifluoride; 10-MDP, 10-methacryloyloxydecyl dihydrogen phosphate.

Sample selection and ethical approval

Twenty-four freshly extracted human mandibular second premolars were collected after patients' informed consent during routine extractions or orthodontic treatments at the Oral Surgery Department, University of Sharjah. The study was designed as a randomised, in vitro, controlled trial. Ethical approval was obtained from the University of Sharjah Research Ethics Committee (Ref: REC-22-10-31-01-S).

Inclusion criteria were: single-rooted premolars with a single canal, closed apices, no cracks, caries, root resorption, or fractures, no congenital anomalies, root length of 14 ± 1 mm, and a post-endodontic residual dentin thickness of at least 1 mm (to simulate flared canals). Exclusion criteria were calcified canals, open apices, severe root curvature, carious lesions, or fractured roots.

Sample size calculation was performed using G*Power software (version 3.1.9.7, Universität Düsseldorf), based on data from a previously published study.[21] The calculated effect size was 1.66, with an alpha error of 0.05 and a beta power of 0.80, yielding a requirement of 7 specimens per group. To account for potential specimen loss, the sample size was increased by 10%, resulting in 8 specimens per group.

Tooth preparation

All samples were cleaned using saline and ultrasonic scalers to remove soft tissue remnants and surface debris. The teeth were then immersed in a 0.1% thymol solution for disinfection. Decoronation was performed at the cementoenamel junction (CEJ) using a diamond long taper bur under copious water cooling, perpendicular to the long axis (Figure 1A). Decoronated roots were stored in distilled water at room temperature for one week before experimentation.

Root canal treatment

The working length was established by inserting a K-file size #15 (Dentsply Sirona, Switzerland) until the file tip was visible at the apex, and confirmed radiographically. Mechanical preparation was performed using rotary files (ProTaper Universal #S1–F3, Dentsply Sirona, Switzerland) in sequence, with intermittent recapitulation using a #15 K-file to maintain apical patency. Irrigation during instrumentation was performed with 3% sodium hypochlorite (Ameclean, Ameya FZE, UAE) and EDTA gel (Charm EDTA Gel, Dentkist Inc., South Korea). Obturation was completed using resin-based sealer (AH Plus, Dentsply Sirona, Switzerland), applied using a lentulo spiral, and size F3 gutta-percha cones (ProTaper Universal, Dentsply Sirona, Switzerland). Gutta-percha cones were inserted to the full working length. Excess gutta-percha was removed using a heated plugger. Radiographs were taken before and after obturation to verify the extension of the master cone and evaluate the quality of the obturation, respectively (Figure 1B).

Post space preparation

After obturation, the samples were stored in distilled water for 24 hours to allow the sealer to set. Post spaces were prepared by removing 9 mm of gutta-percha using Gates Glidden drills, followed by post drills (RelyX Fibre Post drills, 3M Health care, USA) in a standardised sequence from white-banded to blue-banded drills, achieving a final coronal diameter of 1.9 mm. A consistent 9 mm depth was maintained using

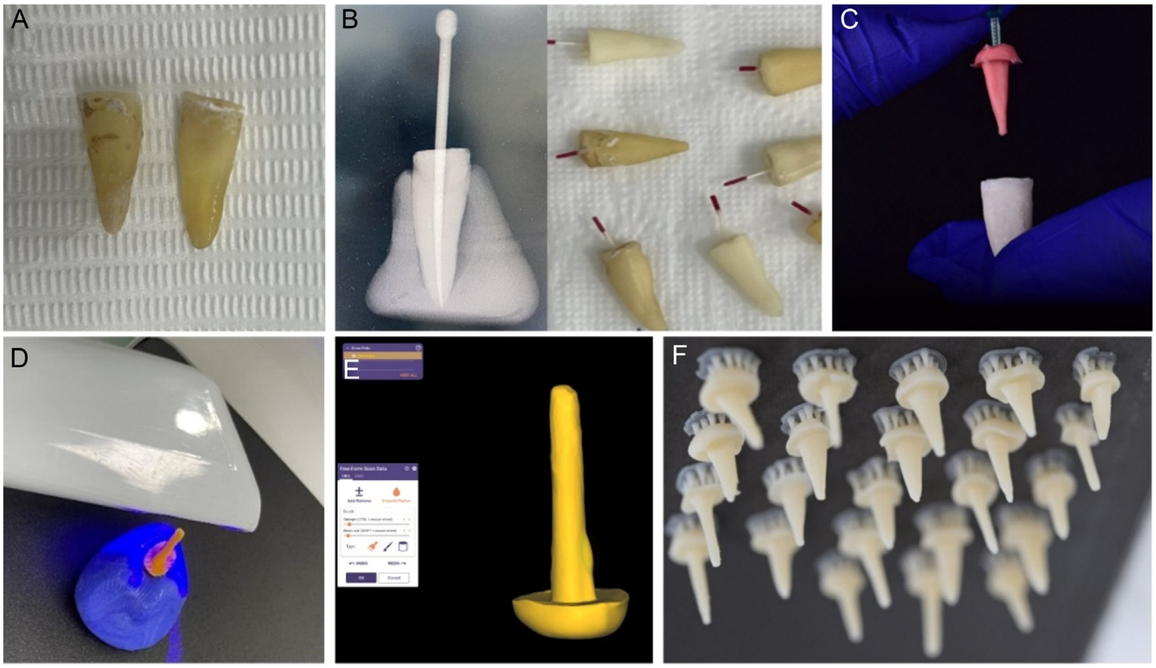

Fig. 1 – Steps of sample preparation: (A) decoronated samples at the CEJ Level, (B) root canal treatment, (C) post space impression with plastic Burnout post, (D) scanning the post space impression with Intraoral scanner, (E) import to Exocad as STL file, (F) 3D-Printed samples.

a rubber stopper, preserving at least 4 mm of the apical gutta-percha. Drill orientation was kept parallel to the canal walls, with intermittent apical pressure applied to prevent ledging or perforation. Following preparation, the canals were irrigated with saline, and radiographs were taken to verify the remaining root thickness. A single operator performed all the procedures to ensure consistency.

Group allocation and impression taking

Samples were randomly divided into three groups (n = 8) using automatic randomisation in an Excel sheet, and assigned to one of the tested fabrication methods: 3D-Printed Posts (3DP), Milled Posts (MP), and Relined Fibre Posts (RFP) as the control group. Post space impressions for 3DP and MP groups were taken using light-body polyvinyl siloxane (Hydrorise Light Body Fast Set, Zhermack, Italy), injected into the canal in an apical to coronal direction to avoid air entrapment. Universal-size plastic burnout posts (Directa AB, Sweden), pretreated with tray adhesive (MPS Tray Adhesive, 3M Healthcare, USA), were inserted into the canals to support the impression material (Figure 1C). After setting and impression removal, the impressions were stabilised coronally using putty silicone (Hydrorise Putty, Zhermack, Italy). Finally, the impressions were inspected under the stereomicroscope to exclude the presence of voids or defects.

Digital scanning and design

The post space impressions were scanned using an intraoral digital scanner (i700, Medit, South Korea) (Figure 1D). The scanned models were then exported as an STL file and processed in CAD software (Exocad Galway v3.0, Exocad GmbH, Germany). Undercuts were smoothed, and the files were further edited in 3D object processing software (MeshMixer v3.5.474, Autodesk, USA), reducing buccolingual and mesiodistal dimensions to 97.5% to allow a 25 ± 5 μm cement space (Figure 1E), as per the protocol reported by Farah et al.[22]

Post fabrication

The posts were fabricated from one of the tested fabrication methods according to the study design listed in Table 2.

3DP Group: STL files were imported into a composer software (version 1.3.2, Asiga). Posts were fabricated from a 3D-printed permanent resin (VarseoSmile Crown Plus, BEGO GmbH, Germany) using a DLP-based 3D printer (Asiga Max, Asiga, Australia), with a layer thickness of 10 μm and a 90° orientation. Supports were placed coronally to avoid distortion of the post surface (Figure 1F). The printed posts were cleaned with alcohol in an ultrasonic bath and a light-emitting diode (LED) dental light-curing unit (LCU) (Cure Box; ODS, South Korea) was used for post-polymerising the 3D printed resin posts.

Table 2 – Study design and grouping of the samples according to the method of fabrication and the tested root third.

Method of fabrication	Tested root thirds		
	Coronal (C)	Middle (M)	Apical (A)
3D-printed posts (3DP)	3DPC	3DPM	3DPA
Milled posts (MP)	MPC	MPM	MPA
Relined fibre posts (RFP)	RFPC	RFPM	RFPA

MP Group: The STL files were milled using hybrid ceramic blocks (Vita Enamic, VITA Zahnfabrik, Germany) using a 5-axis wet milling unit (CORiTEC 450i PRO, Imes-Icore GmbH, Germany).

RFP Group: Fibre Posts (RelyX, 3M Health Care, USA) were cleaned with alcohol pads and silanated with a universal silane primer (Monobond-Plus, Ivoclar Vivadent, Schaan, Liechtenstein). Glycerin-based lubricant (LiquiStrip, Ivoclar Vivadent, Schaan, Liechtenstein) was applied to the canal walls. Bulk-fill flowable composite (Filtek Bulk Fill, 3M Health Care, USA) was injected from apical to coronal direction to minimise voids. Then the posts were inserted and the relining composite was light-cured for 40 seconds using an LED curing unit (Mini LED, Satelec Acteon, France) through the post. Afterwards, RFP posts were removed and inspected for voids and cured again for 20 seconds on each side to ensure maximum polymerisation.

Micro-CT evaluation of internal adaptation

All samples underwent micro-CT scanning (μ CT100, Scanco Medical AG, Zürich, Switzerland) at 90 kV, 200 μA, 20 μm resolution, and 547 ms exposure with a 0.1 mm Cu filter. Each scan produced 750 axial slices over ~48 minutes. The cross-sections' locations, selected for analysis, were standardised, corresponding to the coronal (slice #75), middle (slice #225), and apical (slice #375) thirds of the post space. The average of eight equidistant points per section was used to measure the cement gaps, following the protocol described by (Moustapha et al., 2019) (Figure 2).[23]

Post surface treatment and cementation protocol

After micro-CT analysis, the canals were cleaned with saline and dried using paper points. For 3DP and RFP, the posts' surfaces were sandblasted with 50 μm aluminum oxide at 2 bar pressure, and rinsed with water. On the other hand, MP posts were treated with hydrofluoric acid 5% for 60 seconds, and thoroughly rinsed with water for 10 seconds. All the posts were cleaned in an ultrasonic bath for 30 seconds, then air-dried. A silane primer (Monobond-Plus, Ivoclar Vivadent, Liechtenstein) was applied to all the post surfaces and left to react for 60 seconds, then dried with a gentle stream of air. All samples were cemented using a dual-cure self-adhesive resin cement (RelyX Unicem 2; 3M Health Care, USA). The cement was injected into the canals using the automix tips, and posts were inserted under finger pressure until fully seated in the canal. Light curing was performed through the post for 40 seconds (Mini LED, Satelec Acteon, France). All samples were stored in distilled water for one week for bond maturation before mechanical testing.

Push-out bond strength (PBS) test

Samples were sectioned into 2 mm-thick slices using a low-speed precision sectioning machine (IsoMet 5000, Buehler). Samples were mounted in a universal testing machine (Model

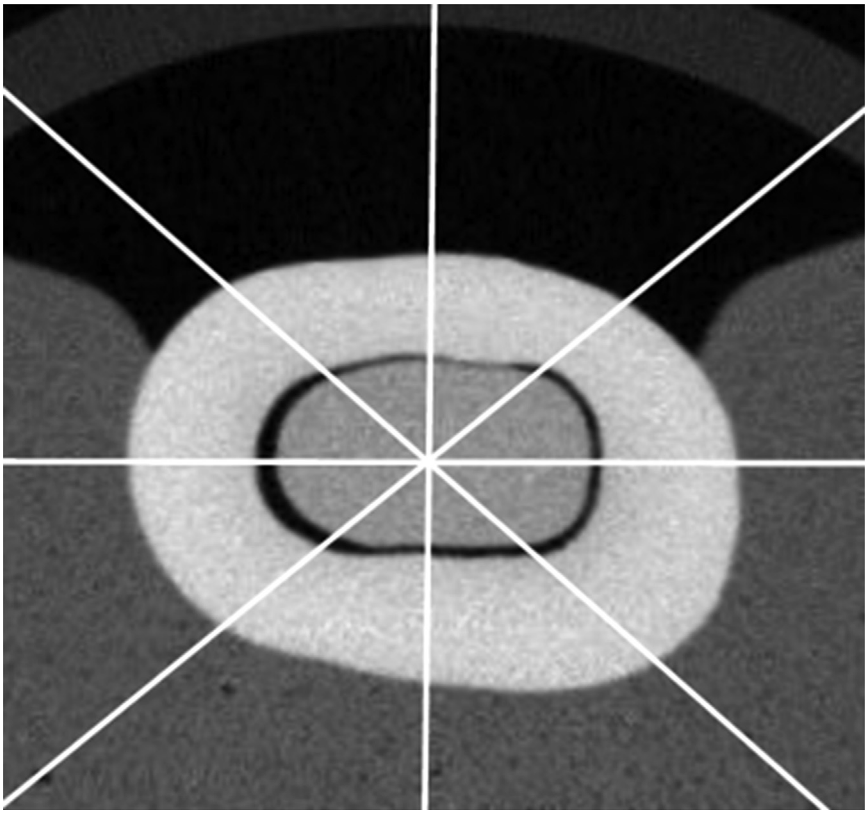

Fig. 2 – Eight points of measurement of the gap in each cross-section.

5ST, Tinius Olsen, USA) using a custom-made jig with the apical side facing the plunger. Afterwards, a compressive load was applied at 1 mm/min till failure, which was defined as a 10% drop from the peak load. The push-out bond strength was calculated using the following formulas:

Bond strength = F/A

Where F is the recorded load at failure in Newtons, and A is the surface area of the bonded interface.

Since the roots were mainly elliptical in cross-section, the major and minor axes of the cement/tooth interface at the coronal and apical surfaces of each root slice were measured with a digital caliper, and the bonded surface area (A) was calculated using the following formula:

$$A = \pi(a_1 + a_2 + b_1 + b_2)\sqrt{h^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2}$$

Where π =3.1416, a_1 and b_1 are the major and minor axes of the apical diameter of the cement/tooth interface ellipse, a_2 *and* b_2 are the major and minor axes of the coronal diameter of the cement/tooth interface ellipse, and h is the vertical height of the root slice.

Statistical analysis

Statistical analysis was performed using SPSS software (v. 29.0, IBM Inc., USA). The normality of the data distributions was assessed with the Shapiro-Wilk test. As all data were found to be normally distributed, parametric testing was employed. The effects of the two independent variables post fabrication technique (3DP, MP, RFP) and root level (coronal, middle, apical) on the dependent variables (internal adaptation and PBS) were analysed using a 2-way analysis of variance (ANOVA). Post-hoc pairwise comparisons were conducted using the Bonferroni correction to identify specific differences between groups. The level for statistical significance was set at $\alpha = 0.05$. Significance level was considered at $P < .05$ (S); while $P < .001$ was considered highly significant (HS).

Results

Internal adaptation (Cement gap)

The two-way ANOVA revealed that the fabrication technique had a highly significant effect on internal adaptation ($P < .001$). As detailed in Table 3, post-hoc analysis confirmed that the relined fibre post (RFP) group yielded a significantly lower mean cement gap value than both the 3D-printed (3DP) and milled (MP) groups (Figure 3A). The difference in adaptation between the 3DP and MP groups was not statistically significant ($P > .05$).

A significant interaction was also found between fabrication technique and root level ($P < .05$), indicating that the effect of root level on adaptation depended on the post type. Specifically, within the 3DP group, the apical third showed significantly poorer adaptation (a larger gap) compared to the

Table 3 – Descriptive statistics of the gap thickness of the tested groups (μm), reflecting their internal adaptation.

Group	N	Mean	SD	SE	95% CI lower	95% CI upper	Minimum	Maximum
3DPC	8	81.7188^{Aa}	17.55409	6.20631	67.0432	96.3943	60.50	103.13
3DPM	8	87.7500^{ABa}	36.89651	13.04457	56.9045	118.5955	58.38	152.75
3DPA	8	142.0156^{Ab}	65.84602	23.28008	86.9670	197.0643	53.63	219.63
MPC	8	120.5156^{B}	18.90855	6.68518	104.7077	136.3236	100.25	160.38
MPM	8	105.0625^{A}	13.42456	4.74630	93.8393	116.2857	87.25	125.13
MPA	8	108.2188^{B}	18.59000	6.57256	92.6771	123.7604	85.25	132.00
RFPC	8	63.8750^{A}	23.70795	8.38203	44.0547	83.6953	37.88	107.38
RFPM	8	61.9219^{B}	25.71330	9.09102	40.4250	83.4187	36.88	93.88
RFPA	8	54.1563^{C}	18.34378	6.48551	38.8205	69.4920	34.75	80.38
Total	72	91.6927	40.26859	4.74570	82.2301	101.1554	34.75	219.63

Within each root section, means with different uppercase superscript letters are statistically different ($p < .05$).
Within each fabrication technique, means with different lowercase superscript letters are statistically different ($P < .05$).

coronal and middle thirds. In contrast, for the RFP group, excellent adaptation was consistently observed across all 3 root levels, with no significant differences noted. Although a significant interaction was observed, the main effect of root level alone was statistically insignificant ($P = .155$) (Figure 3C).

Push-out bond strength

The mean PBS values for all groups are presented in Table 4. Two-way ANOVA revealed no significant effect for the fabrication technique ($P > .05$) on the PBS results, indicating that the overall bond strength was statistically comparable among the three tested groups (Figure 3B).

However, a significant effect was found for the root level ($P = .019$). Overall, the bond strength in the apical thirds was significantly lower than that of the middle thirds ($P < .05$) (Figure 3D). Although the interaction between technique and root level was not statistically significant ($P > .05$), post-hoc comparisons within groups revealed distinct patterns. For the MP group, the bond strength in the apical third was

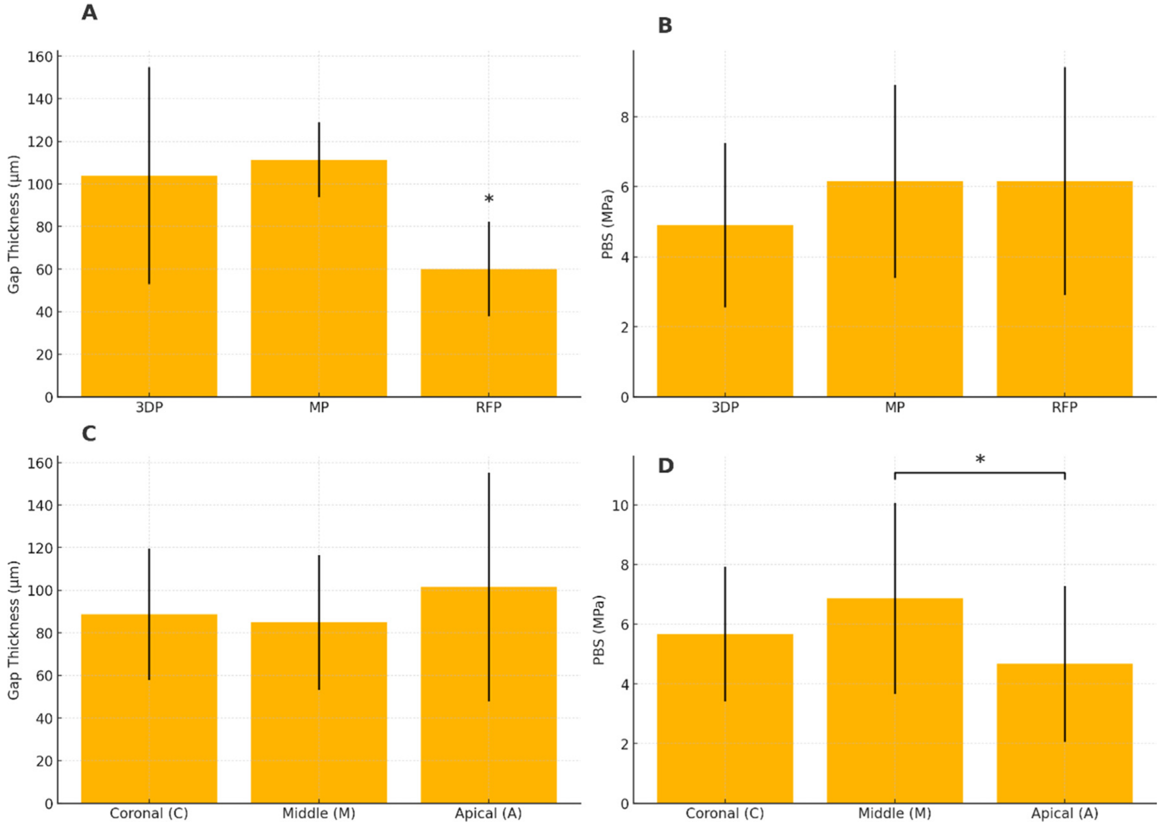

Fig. 3 – Gap thickness and push-out bond strength (PBS) of tested post types and root sections (n = 24 per group/section). (A) Gap thickness of post types (3DP, MP, RFP); * indicates significant difference for RFP. (B) PBS of post types. (C) Gap thickness across root sections (coronal, middle, apical). (D) PBS across root sections. * Indicates significant difference between middle and apical sections, with no difference between coronal and the other sections.

Table 4 – Descriptive statistics of the push-out bond strength tested groups (MPa).

Group	N	Mean	SD	SE	95% CI lower	95% CI upper	Minimum	Maximum
3DPC	8	5.3832	2.48904	0.88001	3.3023	7.4641	2.16	8.35
3DPM	8	4.8065^{B}	2.63544	0.93177	2.6033	7.0098	2.50	8.84
3DPA	8	4.5253	2.11535	0.74789	2.7568	6.2938	3.13	8.63
MPC	8	6.7309^{a}	1.90358	0.67302	5.1395	8.3223	4.67	11.00
MPM	8	7.8196^{Aa}	2.73020	0.96527	5.5371	10.1021	3.74	11.08
MPA	8	3.9183^{b}	2.15210	0.76088	2.1191	5.7175	1.66	7.53
RFPC	8	4.8980^{a}	2.22184	0.78554	3.0405	6.7555	2.62	9.63
RFPM	8	8.0094^{Ab}	3.47068	1.22713	5.1077	10.9111	4.95	14.88
RFPA	8	5.5756^{ab}	3.41920	1.20887	2.7171	8.4342	2.16	11.38
Total	72	5.7408	2.83311	0.33388	5.0750	6.4065	1.66	14.88

Within each root section, means with different uppercase superscript letters are statistically different ($P < .05$).
Within each fabrication technique, means with different lowercase superscript letters are statistically different ($P < .05$).

significantly lower than in the coronal and middle thirds ($P <$ .05), while for the RFP group, the middle third showed significantly higher bond strength than the coronal third ($P < .05$), and for the 3DP group, there were no statistically significant differences in PBS across the three root levels ($P > .05$).

Discussion

This *in vitro* study compared the internal adaptation and PBS of 3 customised post-fabrication techniques: A CAD/CAM 3D-printed resin composite post (3DP), a CAD/CAM milled resin composite post (MP), and a relined fibre post (RFP). The findings revealed that adaptation differed significantly among the fabrication techniques, whereas PBS was not significantly influenced by the fabrication technique but was affected by the root level. Therefore, the null hypothesis was rejected.

Micro-computed tomography (μ-CT) was used in this study to assess cement thickness and internal fit. Compared to conventional sectioning and microscopic analysis, μ-CT offers enhanced 3D visualisation without destroying or slicing samples, ensuring higher reliability and repeatability in measurements and enabling the measurement of the cement thickness at standard points.[24-26]

The superior internal adaptation of the RFP group is consistent with previous studies that highlighted the advantages of direct intra-canal post relining using resin composite; RFP enables a customised fit and produces a thinner and more homogeneous cement layer, which is a critical factor in successful adhesion to radicular dentin by improving adaptation and stress distribution in irregular or flared canals.[7,8,27] A well-adapted post minimises voids, reduces polymerisation shrinkage stress, and enhances retention.[27-29]

In contrast, the relatively larger gaps in the 3DP and MP groups can be attributed to cumulative errors in the indirect CAD/CAM digital workflow, including impression-taking, scanning, data processing, STL file generation, design refinement, or subtractive/additive manufacturing inaccuracies.[23,30,31] Particularly for 3D printing, post-curing shrinkage, resolution limitations, and orientation of printing can influence dimensional accuracy.[15] Indirect scanning of PVS impressions, as used in this study, may introduce inaccuracies compared with direct intraoral scanning, particularly in deep post spaces[14,32] Additionally, reducing the buccolingual and mesiodistal dimensions by 2.5% to allow a 25 ± 5 μm cement space in both milled and 3D-printed posts, thereby facilitating passive seating of the post, may have contributed to the higher gap in the 3DP and MP groups. Nevertheless, the mean cement gaps of the CAD/CAM groups remained within the clinically acceptable range for luted posts.[33,34] The distinct mechanical and physical properties of the tested materials likely played a crucial role in influencing their behavior during the fabrication process. Although Vita Enamic consists of a ceramic network infiltrated with resin, it was selected for this study due to its mechanical characteristics, which more closely resemble those of the tested 3D-printed material (VersioSmile Crown Plus) than those of the CAD/CAM-milled resin matrix–based materials.[18,19]

The pushout bond test is selected in this study as a widely used laboratory technique for assessing the bonding of posts and various adhesive/cementation methods to root dentin. This approach offers the benefits of applying uniform shear tensile stress, fewer early failures due to sectioning procedures, and decreased variability in data.[19,35]

Although the relined fibre posts exhibited significantly better internal adaptation, all 3 fabrication techniques demonstrated statistically comparable PBS values across the different root levels. This supports a growing body of evidence suggesting that while internal adaptation influences cement layer uniformity, its direct correlation to bond strength may be less predictable due to the multifactorial nature of adhesion in root canals.[36,37] This echoes the nuanced understanding that cement layer thickness—although important—interacts with other variables such as canal anatomy, post surface treatments, and adhesive strategies.[38] Mirmohammadi et al.,[39] explained that intermediate cement thickness (80–120 μm) may offer optimal bond strength, while excessively thin or thick layers compromise retention of the posts. Thus, the average cement gaps observed in the MP (~111 μm) and 3DP (~103 μm) groups, which fall within the biomechanically favourable range, may have mitigated the adverse effects of imperfect adaptation and can explain the lack of significant differences in PBS between the three tested groups.

Furthermore, the precementation surface treatment was carefully customised for each post group based on its specific material composition, in accordance with established protocols from previous research. This tailored approach likely contributed to achieving reliable adhesion to the resin cement, which may help explain the statistically comparable PBS values observed among the tested groups. RFP and 3DP posts were sandblasted with 50 μm alumina at 2 bar, roughening the resin composite to increase surface area for resin infiltration and mechanical interlocking.[40] This also exposes filler particles, enhancing chemical bonding with silane and resin cement.[41] Higher pressures or prolonged sandblasting may damage the surface and reduce bond strength.[42] In contrast, MP posts, composed mainly of glass ceramic, were etched with hydrofluoric acid to dissolve the glassy matrix, increasing roughness and micro-retention for stronger micromechanical bonding.[40] Silane primer further enhances chemical adhesion to silicate and composite surfaces.[43,44] Moreover, the self-adhesive dual-cure resin cement used (RelyX Unicem 2) may have contributed to bond reliability through its chemical interaction with hydroxyapatite, moisture tolerance, and reduced technique sensitivity.[45] These standardised protocols may have offset potential disadvantages associated with gap variability and likely regulate bonding performance across groups.[46] Nonetheless, it is encouraging that despite slightly larger cement spaces, both digitally fabricated groups achieved bond strengths statistically comparable to relined fibre posts, suggesting their viability in clinical settings where manual relining may be technique-sensitive or time-consuming.[47] Our results align with previous studies that reported no significant difference in bond strength between CAD/CAM printed and milled posts and custom-relined prefabricated glass fibre posts.[20,48,49] Moreover, the recorded PBS mean values for the RFP and 3DP in our study are similar to those reported by Rodrigues et al.,[50] and Küden et al.[20]

Conversely, some studies have found significant differences between CAD/CAM milled and prefabricated posts, which contradict our findings—but only when the prefabricated fibre posts were used without relining.[51,52] One study attributed the lower bond strength of milled glass fibre posts to their reduced surface roughness and the extensive adjustments required to fit them into the root canal, which compromised adaptation.[51] Another study linked the significantly lower bond strength observed in the non-relined prefabricated group to the increased thickness of the cement layer.[52] Moreover, differences in canal geometry, post materials, post space preparation design, cement types, cementation protocols, and aging or testing conditions may also explain discrepancies between our findings and those reported in the literature. Unfortunately, only one previous study has evaluated the bond strength of 3D-printed posts, which limits the ability to fully justify our findings or directly compare them with existing research.[20]

In the current study, standardised 2 mm-thick slices were used for the PBS test. While previous studies have employed varying thicknesses (eg, 1 mm, 2 mm, and 4 mm), some have suggested that increased thickness may lead to higher push-out forces (N), consistent with the principles of frictional retention. However, Bergoli et al.[53] demonstrated that slice thickness does not significantly influence PBS values when expressed in MPa, indicating that 2 mm slices are suitable for reliable bond strength assessment, particularly as the same thickness was consistently maintained across all tested groups.

Notably, PBS was significantly influenced by the level of the root canal. The apical third consistently exhibited lower bond strength across all groups. This finding is in agreement with prior studies, which indicate that apical dentin has fewer and less organised tubules, thereby reducing adhesive infiltration and hybrid layer formation.[54,55] In addition, reduced accessibility, suboptimal smear layer removal, and limited light penetration in the apical region can impair cement polymerisation. On the contrary, the highest bond strengths were observed in the middle third, likely due to more favorable dentin morphology and ease of cement placement in this region.[37,56]

The limitations of this study include the *in vitro* design, which cannot fully replicate the dynamic intraoral conditions, such as thermal and mechanical cycling, saliva, and occlusal forces. Furthermore, only short-term PBS was assessed. While resin-based materials demonstrated promising mechanical behaviour as coronal restorations,[57] future research should investigate the fracture resistance and long-term performance of CAD/CAM resin-based posts, particularly under conditions involving cyclic loading, aging simulations, and clinical validation through longitudinal trials. In addition, only 1 resin cement and 1 adhesive strategy were tested; alternative cements or pretreatments might yield different results. Comparative studies between direct intraoral and indirect impression scanning workflows for post-fabrication would also be valuable. Finally, further investigations could explore a broader spectrum of 3D-printed and milled resin-based, hybrid, and ceramic CAD/CAM materials for post and core fabrication, potentially offering deeper insights into optimising aesthetic outcomes and clinical performance.

Conclusions

Within the limitations of this in vitro study and the tested materials, it can be concluded that relined fibre posts exhibited the best internal adaptation, producing a thinner and more uniform cement layer than CAD/CAM milled or 3D-printed resin composite posts. However, this superior adaptation did not translate into significantly higher bond strength, as all 3 post systems demonstrated statistically comparable adhesion to root dentin. These findings suggest that 3D printing represents a promising, efficient alternative to milling and relining for post-fabrication, particularly for anatomically complex or flared root canals, where customisation may enhance clinical efficiency. However, further research on the long-term performance of 3DP posts is warranted.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT Scholar in order to help in proofreading and enhance writing style. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Conflict of interest

None disclosed.

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