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Fracture resistance of maxillary lateral incisors: effects of fiber post dimensions, material, and surface treatment

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Abstract

Background Fiber-reinforced posts are widely used to restore endodontically treated anterior teeth, yet the relative contributions of post length, diameter, material, and surface treatment to fracture resistance in maxillary lateral incisors remain unclear.

Purpose To determine the individual and interactive effects of fiber post length, diameter, material, and surface treatment on the fracture resistance and failure modes of endodontically treated maxillary lateral incisors restored with composite cores and monolithic zirconia crowns.

Methods In a controlled laboratory study (2 × 2 × 2 × 2 design; 16 groups; $n = 10$/group; $N = 160$), extracted maxillary lateral incisors received standardized endodontic treatment, fiber post placement, composite core build-ups, and monolithic 5Y-PSZ zirconia crowns. Factors were: post length (8 vs. 12 mm), diameter (0.9 vs. 1.1 mm), post material/system (tested glass-fiber post system vs. tested quartz-fiber post system), and surface treatment (ethanol-cleaned vs. airborne-particle abrasion + silane). A uniform 2-mm ferrule, PDL simulation, and epoxy embedding were used. Specimens were thermocycled (10,000 cycles, 5–55 °C) and loaded at 135° to the long axis with a 3-mm indenter until failure; maximum load (N) and failure mode (repairable vs. non-repairable) were recorded. Data were analyzed with fixed-effects factorial ANOVA (Tukey post hoc) and χ^2 tests ($\alpha = 0.05$).

Results Mean fracture load ranged from 655 ± 62 *N* to 971 ± 65 *N*. Main effects were additive: 12-mm length (+ 86.9 *N*), 1.1-mm diameter (+ 76.7 *N*), the tested quartz-fiber post system (+ 55.0 *N*) and abrasion+silane (+ 36.3 *N*) increased load (all $P \leq .010$), with no interactions (all $P \geq .075$). Higher-strength configurations showed fewer catastrophic root fractures.

Conclusions Within the tested, anatomy-preserving ranges, longer and slightly 1.1 mm diameter posts, the tested quartz-fiber post system and abrasion-plus-silane conditioning can be combined to improve fracture resistance in restored maxillary lateral incisors, supporting strategies that maximise bonding while preserving dentine. Limitation/

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future work: As an in vitro static test with thermal ageing only, cyclic fatigue and long-term interface degradation remain uncertain and should be evaluated in fatigue models and clinical trials.

Keywords Air abrasion, Factorial design, Fiber post, Fracture resistance, Maxillary lateral incisor, Silane, Surface treatment, Zirconia crown

Background

Endodontically treated anterior teeth present a restorative dilemma in which clinicians must balance esthetics, function, and long-term biomechanical integrity. The loss of coronal structure due to caries, fracture, and endodontic access compromises the ability of the tooth to resist functional and parafunctional loads, predisposing it to catastrophic failure. For many decades, intraradicular posts have been used to retain cores and restore form; however, it is now well recognized that posts do not reinforce teeth per se, rather, they can influence how stresses are transferred to the remaining dentin and, consequently, the mode and likelihood of fracture. In the esthetic zone, fiber-reinforced composite posts have largely displaced cast metal and prefabricated metallic posts because of their favorable optical properties and an elastic modulus closer to dentin, which theoretically promotes more homogeneous stress distribution and more repairable failure patterns. Despite widespread clinical adoption, important questions remain about how specific, controllable parameters of fiber post therapy; post length, post width (diameter), post material, and surface treatment, interact to determine fracture resistance in individual tooth types [1–4].

Maxillary lateral incisors are a particularly relevant yet understudied model for this question. Compared with maxillary central incisors, lateral incisors typically exhibit smaller root dimensions, more delicate root morphology, and a higher curvature prevalence, which limits the apical extension and diameter of any post without risking perforation or excessive dentin removal. At the same time, lateral incisors occupy a prominent position in the smile line and often serve as key abutments in adhesive rehabilitations, meaning that both biomechanical and esthetic demands are high. The constrained anatomy of the lateral incisor intensifies the restorative trade-offs inherent in post selection: a longer or wider post may improve retention and reduce coronal lever arms but at the cost of thinning radicular dentin; a stiffer or differently constructed post may shift stress patterns beneficially (or not) depending on the remaining tooth structure, ferrule quality, and cement interface [5–7]. Understanding how length, width, material, and surface treatment each contribute to fracture resistance specifically in lateral incisors can therefore refine clinical decision-making where the margin for error is narrow.

Post length has long been considered a primary factor in post-performance. Traditional guidance has favored extending the post to two-thirds of the root length or at least the crown length, while preserving an adequate apical seal. In fiber post systems, where retention is largely adhesive and frictional contributions are smaller than with parallel-sided metallic posts, the effect of length may be mediated by the available bonding surface and the distribution of tensile and shear stresses along the canal walls. However, excessive length in a slender lateral incisor root may compromise radicular dentin thickness coronally or apically and complicate cementation. Moreover, as fiber posts rely on a bonded complex (post–resin cement–dentin), the quality of the bonded interface and the continuity of the adhesive layer may be as important as absolute length [8–10]. It remains clinically important to clarify whether incremental gains in length translate into meaningful improvements in fracture resistance once a minimal threshold of bonded area and ferrule are achieved.

Post width (diameter) presents a similar double-edged consideration. Increasing diameter increases the cross-sectional area of the post and may increase the stiffness of the post–core complex, potentially reducing coronal deflection under load. Yet, the price is radicular dentin removal, thinning the root and concentrating stresses at the internal line angles of the canal preparation. Preservation of dentin is a consistent predictor of favorable fracture behavior; therefore, clinicians increasingly adopt a "conservative shaping" philosophy, choosing the smallest diameter that allows adequate post fit and core retention [11–13]. Whether a modest increase in diameter within clinically realistic ranges meaningfully changes fracture resistance, and whether such an effect differs among materials and surface preparations, remains a practical question with direct implications for lateral incisor rehabilitation.

Fiber post material encompasses differences in fiber type (e.g., glass, quartz, carbon, or hybrid), fiber volume fraction, orientation, and the epoxy or resin matrix. These compositional differences influence the elastic modulus, strength, translucency, and bonding affinity of the post. Posts with an elastic modulus approximating dentin are theorized to distribute stresses more evenly, reducing peak concentrations that precipitate root fractures; however, not all fiber posts are mechanically equivalent, and some exhibit higher stiffness or distinct failure behaviors. Optical properties also matter in lateral incisors due to thin facial tissues and high esthetic expectations, pushing selection toward glass/quartz fiber posts that better transmit light for resin polymerization and avoid gray shine-through. Whether these material differences translate into measurable gains in fracture resistance, independent of post geometry and bonding, is not fully settled and may depend on the interfacial quality achieved by surface treatment [8, 14].

Surface treatment of fiber posts aims to improve micromechanical interlocking and chemical coupling with resin cements. Common strategies include airborne-particle abrasion to roughen the post surface, tribochemical silica coating to create a silanable surface, hydrogen peroxide or other oxidizing agents to partially dissolve the epoxy matrix and expose fibers, and the application of silane coupling agents to enhance bond strength at the fiber–matrix–cement interface [15–17]. The canal dentin itself may be conditioned with etch-and-rinse or self-etch adhesives, and the choice of resin cement (conventional adhesive resin vs. self-adhesive) introduces further variability. Because the bonded interface is the "weakest link" in the post–dentin complex, improvements in interfacial integrity might be expected to elevate fracture loads and shift failure modes coronally (e.g., core debonding or post pull-out) rather than apically catastrophic root fractures. Yet, aggressive post conditioning could also damage fibers or create stress risers, and not all surface protocols are compatible with all posts or cements. The net effect of surface treatment on fracture resistance in narrow-rooted lateral incisors, where bond area is limited, warrants systematic evaluation [6, 13, 18, 19].

Another critical contextual factor is the ferrule effect, circumferential sound dentin at the crown margin, which is consistently associated with improved fracture resistance and more favorable failure patterns. While the present study standardizes ferrule conditions to isolate the effects of post parameters, it is helpful to interpret any results through the lens of ferrule adequacy because, clinically, post decisions are seldom made in isolation [11]. Occlusal load direction and magnitude, parafunction, crown material, and the presence of residual axial walls further modulate biomechanical outcomes. In vitro testing cannot replicate every clinical nuance, but carefully controlled experiments can identify dominant factors and interactions, especially when factorial designs allow simultaneous evaluation of geometry (length, width), material, and surface treatment combinations within the same tooth type.

The literature contains numerous investigations into fiber posts in anterior teeth, but several gaps persist. Many studies emphasize central incisors or premolars with more generous root dimensions, limiting the generalizability to lateral incisors [20–22]. Others explore single factors in isolation, making it difficult to discern whether apparent benefits of, for example, increased length are contingent on material type or surface protocol. Additionally, few studies report interaction effects explicitly, although clinical decisions inherently involve multiple, interdependent choices. Finally, the distribution of failure modes, repairable versus non-repairable, often matters as much as absolute fracture load for patient-centered outcomes; interventions that increase load capacity but predispose to catastrophic root fractures may be clinically undesirable in slender roots. A comprehensive, multivariate assessment focused on maxillary lateral incisors can therefore provide more practice-relevant guidance than single-factor experiments in dissimilar teeth.

The present study addresses these gaps by evaluating the effect of fiber post length, width, material, and surface treatment, individually and in interaction, on the fracture resistance of endodontically treated maxillary lateral incisors restored with standardized cores and crowns under controlled loading. By restricting the model to a single, clinically challenging tooth type and by employing a factorial design, the study aims to isolate the relative contribution of each parameter within realistic clinical constraints. Outcomes will include maximum fracture load and failure mode classification to distinguish repairable, potentially repairable from non-repairable patterns. The resulting data are intended to inform conservative, anatomy-respectful protocols that maintain dentin where possible while optimizing interfacial integrity and load transfer.

The null hypotheses were that (1) fiber post length within clinically acceptable ranges has no effect on the fracture resistance of maxillary lateral incisors; (2) fiber post width within clinically acceptable ranges has no effect on fracture resistance; (3) fiber post material has no effect on fracture resistance; (4) fiber post surface treatment has no effect on fracture resistance; and (5) there are no interaction effects among length, width, material, and surface treatment on fracture resistance or failure mode distribution.

Methods

Sample size

A priori power analysis (G*Power) for a fixed-effects $2 \times 2 \times 2 \times 2$ ANOVA.

Targets: $\alpha = 0.05$, power $(1-\beta) = 0.80$, conservative effect size $f = 0.25$ ($\eta p^2 \approx 0.058$).

Result: ≥8 specimens per cell (total $N \geq 128$) to detect omnibus effects.

Allowing ~ 15–20% attrition from thermomechanical aging [23], we inflated per-cell n.

Final allocation: 10 teeth per group (16 groups; $N = 160$), balanced design.

This preserves ≥ 0.80 power for main effects and interactions at $f \approx 0.25$.

Table 1 Study groups and subgroups according to fiber post length, diameter, material, and surface treatment

Group	Subgroup
Post Length	8 mm
	12 mm
Post Diameter	0.9 mm
	1.1 mm
Post material/system	glass-fiber
	quartz-fiber
Post surface treatment	alcohol
	APA + silane

Study design and factors

A controlled, laboratory experiment was conducted with 4 fixed factors: post length (short vs. long), post diameter (narrow vs. standard), post material/system (glass-fiber vs. quartz-fiber), and post surface treatment (alcohol only vs. airborne-particle abrasion + silane) (Table 1). Sixteen groups were formed; each group contained 10 specimens ($n = 160$ total). The primary outcome was maximum fracture load (N). Secondary outcomes were failure mode classification and the distribution of non-catastrophic versus catastrophic failure outcomes.

Length: 8 mm (short) vs. 12 mm (long) measured from the canal orifice, leaving ≥ 5 mm apical gutta-percha seal.

- Diameter: 0.9 mm (narrow) vs. 1.1 mm (standard) corresponding to manufacturer drills; the selected sizes were within the native canal diameter to minimize dentin removal.
- Post material/system: Prefabricated fiber posts of either glass-fiber (X-Post, Dentsply Sirona, Switzerland) or quartz-fiber (D.T. Light-Post, RTD, France). Because two commercially available post systems were used, this factor was considered as post material/system rather than fiber material alone, as the posts may differ not only in fiber composition but also in manufacturer-specific geometry, taper, fiber arrangement, matrix composition, and proprietary design.
- Surface treatment:

1. Control: alcohol only, no mechanical pretreatment.
2. Airborne-particle abrasion (50 µm Al_2O_3, 2.5 bar, 10 s, 10 mm distance, continuous sweeping) followed by ethanol rinse, air-dry, and silane (60 s dwell) before adhesive/primer.

Randomization to groups was computer-generated. Specimen preparation and testing were performed by calibrated operators; the examiner classifying failures was blinded to group allocation (Fig. 1).

Specimen selection and storage

One hundred sixty freshly extracted, single-rooted human maxillary lateral incisors free of caries, cracks, restorations, resorption, or previous endodontic treatment were collected under informed consent. Teeth with root curvature > 10° (Schneider method) or visible craze lines under ×10 magnification (10× magnifying loupe, SurgiTel, USA) were excluded. Buccolingual and mesiodistal root dimensions at 7 mm apical to the CEJ were measured with a digital caliper; outliers (± 10% of mean) were replaced to reduce anatomical variability. Teeth were cleaned of soft tissue and calculus with ultrasonic scalers (Cavitron, Dentsply Sirona, USA) and stored in 0.1% thymol (Thymol, Sigma-Aldrich, USA) at 4 °C for

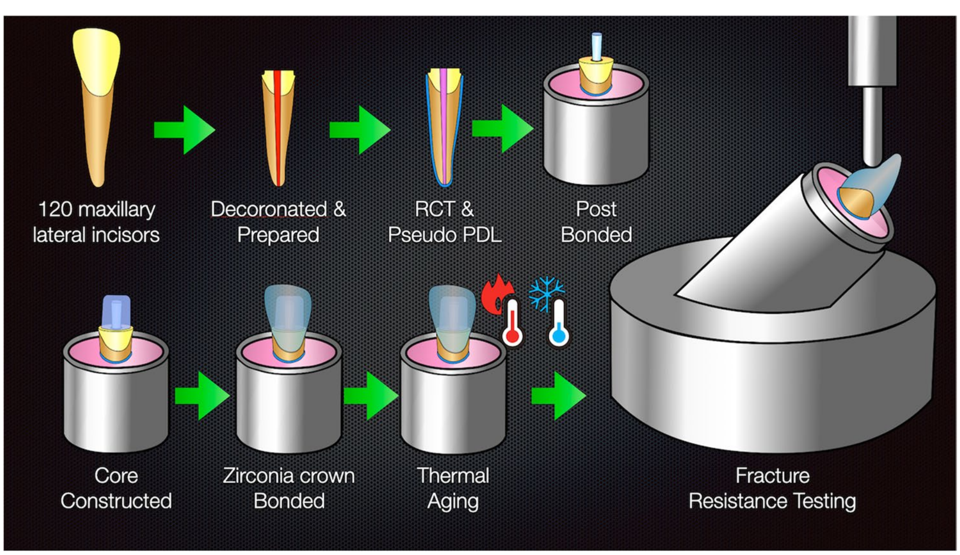

Fig. 1 Flow chart showing the allocation of specimens according to the 2 × 2 × 2 × 2 factorial design. The tested variables were post length, post diameter, post material, and post surface treatment, resulting in 16 experimental groups with 10 specimens per group

≤ 3 months until use, then rehydrated in distilled water at 37 °C for 24 h before preparation.

Crown preparation and ferrule standardization

Each tooth was decoronated perpendicular to the long axis 2 mm coronal to the CEJ, producing a uniform 2-mm circumferential ferrule of sound dentin after subsequent preparation (Fig. 2). A standardized full-coverage preparation was performed with a custom high-precision jig to ensure consistent convergence (6° total occlusal convergence), finish line (0.4 mm deep rounded shoulder), and incisal reduction (1.5 mm). Internal line angles were rounded. Finish lines were kept 1 mm supragingival relative to the original CEJ. All preparations were verified with silicone reduction guides.

Periodontal ligament simulation and embedding

A thin PDL analog (Ghenesyl, Fast Set Light Body, LASCOD SpA, Italy) was applied to the root surface up to 2 mm below the finish line using a dip-coating technique and allowed to set within an impression mold. Teeth were then embedded in autopolymerizing epoxy resin blocks (Axcent Orthodontic Acrylic, Garreco Dental, USA), leaving 2 mm of root exposed coronal to the resin to simulate bone crest level [4]. The long axis of the tooth was oriented at 45° to the horizontal to facilitate 135° palatal loading relative to the incisal edge during testing.

Endodontic treatment

Standardized endodontic access cavities were prepared. Working length was established to the apical foramen. Canals were shaped with NiTi rotary instruments to size 35/0.04. (One Curve, Micro-Mega, Coltene, France) Irrigation was performed with 2.5% NaOCl (Chloraxid 2%, Cerkamed, Poland) throughout instrumentation, followed by a final sequence of 5 mL 17% EDTA (Endo-Solution, Cerkamed, Poland)for 60 s, 5 mL 2.5% NaOCl, and 5 mL distilled water. Canals were dried with paper points (ROEKO Paper Points, Coltene, Germany). Warm vertical condensation of gutta-percha (Roeko Gutta-Percha Points, Coltene, Germany)with an epoxy resin sealer (AH Plus, Dentsply Sirona, Switzerland) was used to create apical plugs only, intentionally leaving the coronal canal space for the post so that no de-obturation was required. Coronal access cavities were temporarily sealed with glass ionomer (Ketac Molar, 3 M, USA), and specimens were stored at 37 °C in 100% humidity for 7 days to allow complete sealer set.

Fig. 2 Decoronated lateral incisor

Post-space preparation

Post space was prepared with the manufacturer's dedicated drills for each post system according to the assigned group: post length (8–12 mm), post diameter (0.9–1.1 mm), and post material, either glass fiber posts (X-Post, Dentsply Sirona, Switzerland) or quartz fiber posts (D.T. Light-Post, RTD, France). At least 5 mm of apical gutta-percha was preserved in all specimens. Preparation respected the canal anatomy; no flaring beyond the dedicated drill was permitted. If the canal was narrower than the assigned post/drill combination, the specimen was replaced at this stage. Canal walls were irrigated with 5 mL distilled water, followed by 5 mL 17% EDTA (Endo-Solution, Cerkamed, Poland) for 30 s and a final 5 mL distilled water rinse; canals were gently dried with paper points (ROEKO Paper Points, Coltene, Germany).

Post surface conditioning and bonding

Posts received the allocated surface protocol. For the control protocol, posts were cleaned with ethanol (Ethyl Alcohol 70%, El-Nasr Pharmaceutical Chemicals, Egypt) and air-dried.

For the abrasion + silane protocol, airborne-particle abrasion was applied using 50 µm Al_2O_3 (Korox 50, Bego, Germany), 2.5 bar, 10 s, 10 mm distance. Posts were ultrasonically cleaned in ethanol (Ethyl Alcohol 70%, El-Nasr Pharmaceutical Chemicals, Egypt) for 2 min, air-dried, silanated (Monobond N, Ivoclar Vivadent, Liechtenstein) for 60 s, then gently air-dried.

Canal bonding followed a standardized adhesive resin cement protocol: A dual-cure self-adhesive resin cement (RelyX U200, 3 M, USA) was used according to the manufacturer's instructions. Canals were cleaned using alcohol. Cement was injected into the canal using a root canal tip to minimize voids. The post was coated with cement and inserted to full depth under steady pressure. Excess cement was removed using microbrush, and the coronal interface was light-cured from multiple directions (at least 40 s total) (Fig. 3).

Composite core build-up

A standardized dual-cure core composite (Rebilda DC, VOCO, Germany) was used with a transparent core former (Crown Forms, TDV, Brazil) to produce a

Fig. 3 Cemented fiber post inside the prepared post space of a maxillary lateral incisor

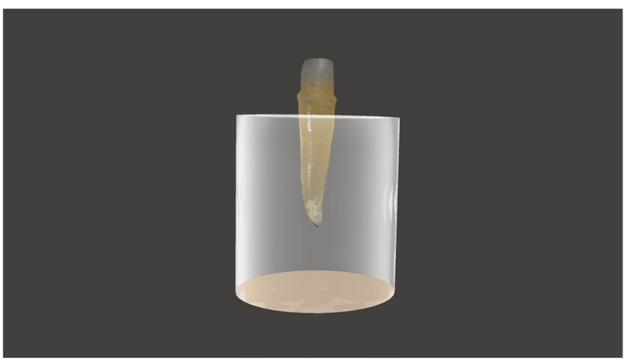

Fig. 4 Composite core build-up fabricated over the cemented fiber post

Fig. 5 5-mm-high core was constructed using standardized dual-cure core composite

5-mm-high core. The coronal fiber post was wiped with ethanol, lightly air-dried, and universal adhesive (Futurabond U, VOCO, Germany) was applied to root surface with microbrushes (20 s), air-thinned, and light-cured (10 s). Core composite was placed in ≤ 2 mm increments and light-cured (20 s per increment) with a LED light (Bluephase N, Ivoclar Vivadent, Liechtenstein) at ≥ 1000 mW/cm². Final curing: 40 s from four directions. The core was finished with fine diamond burs (Komet, Gebr. Brasseler, Germany) to remove flash and to standardize height relative to a reference jig (Figs 4 and 5).

Fig. 6 Monolithic zirconia crown cemented over the standardized post-and-core foundation

Digital workflow and zirconia crowns

Digital intraoral scans of each core-prepared tooth were obtained. Monolithic 5Y-PSZ zirconia crowns were selected to standardize the definitive coronal restoration, provide an esthetic full-coverage material relevant to anterior teeth, and eliminate variability related to veneering ceramic fracture or bilayer crown design. Monolithic cubic zirconia 5Y-PSZ crowns (Katana Zirconia UTML, Kuraray Noritake Dental, Japan) were designed with standardized parameters: cement space 60 µm (initiating 1 mm above the margin), minimum axial thickness 1.0 mm, incisal thickness 1.5 mm, and a 3-mm-diameter palatal contact area to standardize load application. Crowns were milled (inLab MC X5, Dentsply Sirona, Germany), sintered per the manufacturer's schedule, and finished/polished.

For proper zirconia intaglio treatment, internal surfaces were airborne-particle abraded with 50 µm Al_2O_3 (Korox 50, Bego, Germany), 2.5 bar, 10 s, 10 mm distance. Ultrasonically cleaned in ethanol (Ethyl Alcohol 70%, El-Nasr Pharmaceutical Chemicals, Egypt) for 2–3 min, thoroughly air-dried with oil-free air, then primed with an MDP-containing zirconia primer (Clearfil Ceramic Primer Plus, Kuraray Noritake Dental, Japan) for 60 s dwell, gentle air-thin. Restorations were kept uncontaminated until bonding.

Crown bonding

Crowns were bonded using a dual-cure self-adhesive resin cement (RelyX U200, 3 M, USA) to eliminate variability from tooth-side adhesives at this stage. Cement was applied to the intaglio, crowns were seated under a standardized axial load of 50 N for 5 min using a loading device to control film thickness, excess cement was removed at gel stage, and margins were light-cured (20 s per surface). Specimens were stored at 37 °C in distilled water for 24 h before aging (Fig. 6).

Thermal aging

All specimens underwent standardized thermal aging (THE-1100, SD Mechatronik, Germany) for 10,000 cycles between 5 °C and 55 °C, 30-s dwell, 10-s transfer.

Fracture resistance testing

After aging, specimens were mounted in a universal testing machine (Instron, Instron Corp., USA). A 3-mm-diameter stainless-steel indenter applied compressive load to the standardized palatal contact point at 135° to the long axis, representing a standardized oblique palatal loading direction used to simulate anterior incisal guidance, where maxillary anterior teeth are commonly subjected to non-axial forces. This loading configuration was selected to generate a clinically relevant stress pattern within the crown–core–post–root complex and has been used in previous in vitro studies evaluating fracture resistance of restored anterior teeth [25, 26]. Crosshead speed was 1.0 mm/min until catastrophic failure, defined by a sudden load drop accompanied by visible cracking/sound. Maximum load at failure (*N*) was recorded. Indenter and specimen were kept wet during testing to reduce frictional heat.

Failure mode analysis

Post-fracture, specimens were examined under a stereomicroscope (SZ61, Olympus, Japan). Failure modes (Fig. 7) were classified as:

- Type I: crown fracture without root fracture (repairable) (Fig. 8).
- Type II: post fracture or core fracture or debonding (repairable).
- Type III: coronal/root fracture above simulated bone level (potentially repairable).
- Type IV: vertical/root fracture below simulated bone level (catastrophic, non-repairable).

Representative failures were analyzed. Although predefined categories and blinded assessment were used to reduce classification bias, formal inter-examiner reproducibility testing was not performed; therefore, failure-mode findings should be interpreted cautiously and future studies should include inter-examiner agreement assessment.

Statistical analysis

Normality was assessed using the Shapiro–Wilk test and by visual inspection of Q–Q plots of the model residuals. Homogeneity of variance was evaluated using Levene's test and residual-versus-fitted plots. Standardized residuals were reviewed to identify potential outliers or influential observations. Because each extracted tooth represented a single independent experimental unit and specimens were randomly allocated to groups, no repeated-measurement or clustered data structure was present.

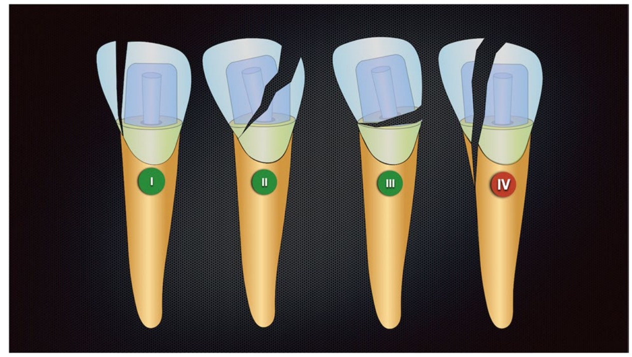

Fig. 7 Diagram of failure modes

Fig. 8 Representative Type I failure pattern after fracture resistance testing

Fracture load data were analyzed using fixed-effects four-way factorial ANOVA to test the main effects of post length, post diameter, post material/system, surface treatment, and their interaction effects. When appropriate, Tukey post hoc comparisons were used. Failure mode distributions and non-catastrophic versus catastrophic failure outcome proportions were compared using the χ^2 test. Significance was set at $\alpha = 0.05$. Statistical software (IBM SPSS Statistics Version 28, IBM Corp., USA) was specified a priori.

Results

The assumptions for factorial ANOVA were considered acceptable. Shapiro–Wilk testing and visual inspection of Q–Q plots did not indicate marked deviation from normality of residuals, and Levene's test together with residual-versus-fitted plots did not indicate substantial heteroscedasticity. No influential outliers were identified from standardized residual inspection.

All 160 specimens completed thermocycling and load-to-failure testing and were included in the analysis (16 groups; $n = 10$ per group) (Table 2). Fracture load varied across the 16 experimental combinations. The lowest

Table 2 Fracture load by post length, diameter, material, and surface treatment (*n* = 10/group)

Group	Length (mm)	Diameter (mm)	Material/System	Surface treatment	Mean ± SD (*N*)	Median (IQR) (*N*)	Min–Max (*N*)
1	8	0.9	Glass	Alcohol	654.8 ± 62.4	651.1 (58.6)	535.9–759.9
2	8	0.9	Glass	Air abrasion + silane	694.5 ± 40.4	698.6 (42.4)	626.0–740.5
3	8	0.9	Quartz	Alcohol	689.3 ± 86.1	675.9 (80.6)	541.3–821.9
4	8	0.9	Quartz	Air abrasion + silane	760.0 ± 73.1	742.7 (111.5)	656.5–867.1
5	8	1.1	Glass	Alcohol	735.7 ± 79.0	742.9 (79.1)	622.8–886.1
6	8	1.1	Glass	Air abrasion + silane	808.9 ± 51.6	816.7 (70.0)	701.7–893.2
7	8	1.1	Quartz	Alcohol	807.3 ± 80.1	800.7 (114.1)	709.6–960.2
8	8	1.1	Quartz	Air abrasion + silane	877.3 ± 56.7	865.6 (69.7)	812.7–981.4
9	12	0.9	Glass	Alcohol	735.8 ± 66.9	718.0 (91.3)	650.3–852.3
10	12	0.9	Glass	Air abrasion + silane	801.9 ± 51.4	805.4 (60.2)	718.0–879.7
11	12	0.9	Quartz	Alcohol	810.3 ± 73.1	824.4 (84.7)	686.1–926.0
12	12	0.9	Quartz	Air abrasion + silane	847.0 ± 47.3	846.4 (69.1)	764.5–913.8
13	12	1.1	Glass	Alcohol	850.2 ± 35.9	854.7 (44.0)	790.1–893.4
14	12	1.1	Glass	Air abrasion + silane	856.3 ± 45.5	861.4 (53.1)	777.2–922.4
15	12	1.1	Quartz	Alcohol	938.0 ± 67.8	936.2 (74.9)	827.8–1053.1
16	12	1.1	Quartz	Air abrasion + silane	971.1 ± 64.6	970.7 (79.1)	874.0–1071.2

Table 3 Main effects of post parameters on fracture load (collapsed across other factors; *n* = 80 per level)

Factor	Level	*n*	Mean ± SD (*N*)	Mean difference (Level2–Level1) (*N*)	95% CI (*N*)	*P* value
Length	8 mm	80	745.9 ± 92.0	+ 86.9	59.8 to 114.0	< 0.001
	12 mm	80	832.8 ± 81.4	+ 86.9	59.8 to 114.0	< 0.001
material/system	0.9 mm	80	749.2 ± 86.2	+ 76.7	49.3 to 104.2	< 0.001
	1.1 mm	80	825.9 ± 93.3	+ 76.7	49.3 to 104.2	< 0.001
Material	Glass	80	767.3 ± 85.2	+ 55.0	27.2 to 82.8	< 0.001
	Quartz	80	822.3 ± 98.1	+ 55.0	27.2 to 82.8	< 0.001
Surface	Alcohol	80	790.2 ± 101.7	+ 36.3	8.9 to 63.8	0.010
	Air abrasion + silane	80	826.5 ± 79.1	+ 36.3	8.9 to 63.8	0.010

mean fracture load was recorded for the 8-mm/0.9-mm/glass/alcohol group (Group 1: 654.8 ± 62.4 *N*), whereas the highest mean fracture load was recorded for the 12-mm/1.1-mm/quartz/airborne-particle abrasion plus silane group (Group 16: 971.1 ± 64.6 *N*) (Table 2). Across groups, fracture load generally increased with longer post length, 1.1 diameter, the tested quartz-fiber post system, and airborne-particle abrasion plus silanization.

When data were collapsed by factor level, 12-mm posts showed significantly greater fracture load than 8-mm posts (832.8 ± 81.4 *N* versus 745.9 ± 92.0 *N*; mean difference, 86.9 *N*; 95% confidence interval [CI], 59.8 to 114.0; *P*<.001) (Table 3). Similarly, 1.1-mm posts showed significantly greater fracture load than 0.9-mm posts (825.9 ± 93.3 *N* versus 749.2 ± 86.2 *N*; mean difference, 76.7 *N*; 95% CI, 49.3 to 104.2; *P*<.001) (Table 3). The tested quartz-fiber system also produced significantly higher fracture load than glass-fiber posts (822.3 ± 98.1 N versus 767.3 ± 85.2 N; mean difference, 55.0 N; 95% CI, 27.2 to 82.8; *P*<.001) (Table 3). In addition, airborne-particle abrasion plus silane pretreatment resulted in significantly higher fracture load than alcohol cleaning alone (826.5 ± 79.1 *N* versus 790.2 ± 101.7 *N*; mean difference, 36.3 *N*; 95% CI, 8.9 to 63.8; *P*=.010) (Table 3).

Table 4 Four-way factorial ANOVA (Load ~ Length × Diameter × Material × Surface), α = 0.05

Source	df	F	*P* value	Partial η^2
Length (L)	1	88.82	< 0.001	0.382
Diameter (D)	1	97.22	< 0.001	0.403
material/system (M)	1	22.12	< 0.001	0.133
Surface (S)	1	65.56	< 0.001	0.313
L×D	1	0.03	0.870	0.000
L×M	1	1.11	0.294	0.008
L×S	1	0.60	0.441	0.004
D×M	1	1.40	0.239	0.010
D×S	1	3.07	0.082	0.021
M×S	1	3.21	0.075	0.022
L×D×M	1	0.60	0.440	0.004
L×D×S	1	0.54	0.463	0.004
L×M×S	1	0.91	0.343	0.006
D×M×S	1	3.22	0.075	0.022
L×D×M×S	1	1.15	0.285	0.008

Four-way factorial ANOVA demonstrated significant main effects for all tested factors: post length (F = 88.82, *P*<.001; partial η^2=0.382), post diameter (F = 97.22, *P*<.001; partial η^2=0.403), post material/system (F = 22.12, *P*<.001; partial η^2=0.133), and surface treatment (F = 65.56, *P*<.001; partial η^2=0.313) (Table 4).

Table 5 Failure mode distribution by experimental group (*n* = 10 each). Type I and Type II = repairable/favorable; Type III = potentially repairable/conditionally restorable; Type IV = catastrophic/non-repairable. The combined Types I-III column is presented only as a non-catastrophic laboratory outcome category and does not indicate that all Type III fractures are definitively repairable

Group	L	D	M	S	Type I *n* (%)	Type II *n* (%)	Type III *n* (%)	Type IV *n* (%)	Non-catastrophic I-III *n* (%)
1	8	0.9	Glass	Alcohol	2 (20)	2 (20)	1 (10)	5 (50)	5 (50)
2	8	0.9	Glass	Abrasion+silane	2 (20)	2 (20)	1 (10)	5 (50)	5 (50)
3	8	0.9	Quartz	Alcohol	2 (20)	2 (20)	1 (10)	5 (50)	5 (50)
4	8	0.9	Quartz	Abrasion+silane	3 (30)	2 (20)	2 (20)	3 (30)	7 (70)
5	8	1.1	Glass	Alcohol	3 (30)	2 (20)	1 (10)	4 (40)	6 (60)
6	8	1.1	Glass	Abrasion+silane	4 (40)	2 (20)	1 (10)	3 (30)	7 (70)
7	8	1.1	Quartz	Alcohol	4 (40)	2 (20)	1 (10)	3 (30)	7 (70)
8	8	1.1	Quartz	Abrasion+silane	5 (50)	3 (30)	0 (0)	2 (20)	8 (80)
9	12	0.9	Glass	Alcohol	3 (30)	2 (20)	1 (10)	4 (40)	6 (60)
10	12	0.9	Glass	Abrasion+silane	4 (40)	2 (20)	1 (10)	3 (30)	7 (70)
11	12	0.9	Quartz	Alcohol	4 (40)	2 (20)	1 (10)	3 (30)	7 (70)
12	12	0.9	Quartz	Abrasion+silane	4 (40)	3 (30)	1 (10)	2 (20)	8 (80)
13	12	1.1	Glass	Alcohol	4 (40)	3 (30)	1 (10)	2 (20)	8 (80)
14	12	1.1	Glass	Abrasion+silane	4 (40)	3 (30)	1 (10)	2 (20)	8 (80)
15	12	1.1	Quartz	Alcohol	5 (50)	3 (30)	1 (10)	1 (10)	9 (90)
16	12	1.1	Quartz	Abrasion+silane	5 (50)	3 (30)	1 (10)	1 (10)	9 (90)

Table 6 Association between study factors and non-catastrophic failure outcome category; chi-square tests for combined Types I-III versus catastrophic Type IV failure. Type III failures were considered potentially repairable/conditionally restorable, not definitively repairable

Factor	Level 1 vs. Level 2	Non-catastrophic I-III, Level 1 *n* (%)	Non-catastrophic I-III, Level 2 *n* (%)	χ^2 (df = 1)	*P* value	Odds ratio (95% CI)
Length	8 mm vs. 12 mm	50/80 (62.5)	62/80 (77.5)	4.29	0.038	2.07 (1.03–4.13)
Diameter/Syetem	0.9 mm vs. 1.1 mm	50/80 (62.5)	62/80 (77.5)	4.29	0.038	2.07 (1.03–4.13)
Material	Glass vs. Quartz	52/80 (65.0)	60/80 (75.0)	1.90	0.168	1.62 (0.82–3.20)
Surface	Alcohol vs. Air abrasion + silane	53/80 (66.3)	59/80 (73.8)	1.07	0.301	1.43 (0.72–2.83)

No significant 2-way, 3-way, or 4-way interactions were detected (all *P*≥.075), indicating that the effects of the tested variables were largely additive within the evaluated ranges (Table 4).

Failure mode analysis showed a trend toward a greater proportion of favorable/repairable Type I and Type II failures and fewer catastrophic Type IV failures in groups with higher fracture resistance (Table 5). Type III failures were reported separately as potentially repairable/conditionally restorable and were not interpreted as definitively repairable. For descriptive comparison, combined non-catastrophic outcomes (Types I-III) were 50% in the lowest-performing groups (Groups 1–3) and increased to 90% in the highest-performing groups (Groups 15 and 16) (Table 5). Overall group-level distributions indicated fewer catastrophic Type IV failures in combinations incorporating longer posts, 1.1-mm diameter, and quartz-fiber posts, particularly when paired with airborne-particle abrasion plus silane (Table 5).

When failure outcomes were analyzed by factor level as combined non-catastrophic outcomes (Types I-III) versus catastrophic Type IV failures, significant associations were found for post length (χ^2=4.29, *P*=.038; OR = 2.07; 95% CI, 1.03 to 4.13) and post diameter (χ^2=4.29, *P*=.038; OR = 2.07; 95% CI, 1.03 to 4.13), with 12-mm posts and 1.1-mm posts showing higher proportions of non-catastrophic outcomes. No significant associations were found for post material (*P*=.168) or surface treatment (*P*=.301) (Table 6). This analysis was used only to distinguish catastrophic from non-catastrophic laboratory failure patterns and should not be interpreted as evidence that all Type III fractures are clinically repairable. These findings should therefore be interpreted as laboratory-based failure classifications rather than direct clinical evidence of restorability.

Discussion

The present study evaluated the independent and combined effects of fiber post length, diameter, material, and surface treatment on the fracture resistance and failure mode of endodontically treated maxillary lateral incisors restored with composite cores and monolithic zirconia crowns. Within the limitations of this in vitro investigation, all 4 main factors significantly influenced fracture load, whereas no statistically significant interaction effects were identified in the factorial ANOVA.

In general, longer posts (12 mm), greater diameter (1.1 mm), the tested quartz-fiber post system, and airborne-particle abrasion followed by silanization were associated with higher fracture resistance values than their respective counterparts [16, 24–26].

A principal finding of this study was the significant effect of post length on fracture resistance, with 12-mm posts demonstrating higher mean fracture loads than 8-mm posts. This finding is biomechanically plausible because increased post length increases the bonded surface area and may improve stress distribution along the root canal walls, thereby reducing stress concentration in the coronal root region. In slender roots such as maxillary lateral incisors, however, the clinical relevance of increasing post length must be balanced against preservation of apical seal and the risk of overextension in curved canals [26–28]. The present results suggest that, when an adequate apical seal is maintained and canal anatomy permits, a longer fiber post can improve mechanical performance without necessarily changing the interaction pattern with other post variables.

Post diameter also had a significant effect, with the 1.1-mm posts producing greater fracture resistance than the 0.9-mm posts. This may be attributed to increased cross-sectional stiffness of the post-core complex and reduced coronal deflection during oblique loading. However, this finding should be interpreted cautiously and only within the conservative diameter range tested in the present in vitro study. Although the selected post diameters were considered compatible with the native canal anatomy and specimens with inadequate dentin dimensions were excluded, the remaining radicular dentin thickness was not directly quantified using micro-CT because the device was not available during the study period. In addition, stress distribution was not evaluated using finite element analysis. Therefore, the observed benefit of the 1.1-mm post diameter should not be generalized to aggressive canal enlargement. Clinically, post diameter selection should remain conservative and guided primarily by preservation of radicular dentin, especially in maxillary lateral incisors with narrow roots [14, 29–31].

The tested quartz-fiber post system demonstrated significantly higher fracture loads than the tested glass-fiber post system in the present study. However, this finding should be interpreted as a post material/system effect rather than an isolated fiber-composition effect. Although both systems were standardized as much as possible regarding post length and diameter, the two commercially available post systems may differ in taper, geometry, fiber volume, fiber orientation, matrix composition, translucency, and manufacturer-specific design. These characteristics may have contributed to the observed differences in fracture resistance. Therefore, the present results should not be interpreted as evidence that quartz fiber composition alone is superior to glass fiber composition, but rather that the tested quartz-fiber post system performed better than the tested glass-fiber post system under the specific experimental conditions of this study. Future investigations using matched or custom-fabricated posts with identical geometry and internal configuration are recommended to isolate the independent effect of fiber type more precisely.

Surface treatment was another significant determinant of fracture resistance in the factorial ANOVA, with airborne-particle abrasion plus silane outperforming the alcohol-cleaned control. This supports the concept that improving post-cement interfacial integrity can enhance overall resistance to fracture in bonded post-core systems. Surface roughening may increase micromechanical retention, while silanization may improve chemical coupling at the fiber/resin interface, thereby reducing interfacial defects and stress concentration during loading. Although the collapsed means showed a moderate improvement, the effect size was clinically relevant given the constrained anatomy and reduced bonding substrate typical of lateral incisors. The absence of a statistically significant interaction with post material or diameter suggests that this protocol may provide a broadly useful enhancement rather than a material-specific effect under the present conditions [32–35].

An important strength of this study was the use of a 2 × 2 × 2 × 2 factorial design, which permitted simultaneous evaluation of multiple clinically relevant variables and their interactions in a single tooth type. Many previous laboratory investigations have evaluated post characteristics in isolation or in different tooth categories, limiting direct clinical translation [20, 21, 36, 37]. By focusing specifically on maxillary lateral incisors, the current study addressed a tooth with relatively narrow roots and high esthetic demand, in which restorative decisions are especially technique-sensitive. The lack of statistically significant interaction effects suggests that, within the tested ranges, the contribution of each factor is largely additive. Clinically, this may simplify decision-making because gains from optimized length, diameter, material, and surface treatment appear to accumulate rather than depend on a specific combination.

Failure mode analysis adds clinically relevant context beyond fracture load alone. Higher-performing groups generally showed a greater proportion of repairable/favorable Type I and Type II failures, while Type III failures were considered potentially repairable/conditionally restorable and were interpreted separately from clearly repairable failures. Fewer catastrophic/non-repairable Type IV root fractures were observed in the higher-performing combinations. This pattern is clinically relevant because restorability is often more important than absolute load capacity in anterior teeth. However, Type III coronal/root fractures should not be considered universally repairable, because clinical management depends on the fracture level, periodontal bone level, remaining tooth structure, and feasibility of isolation and restoration. Therefore, the categorical findings should be interpreted cautiously given the sample size per group and the laboratory nature of the outcome. In addition, although predefined criteria and blinded assessment were used, formal inter-examiner reproducibility testing was not performed; this should be considered when interpreting the failure-mode distribution and should be addressed in future studies.

This study has several limitations. First, it was an in vitro investigation using monotonic static load-to-failure testing; therefore, it does not fully reproduce the cyclic, multidirectional, and long-term forces that occur clinically. Although thermal aging and standardized 135° oblique loading were used, the model remains a laboratory simplification and does not simulate clinical variations in occlusal contacts, mandibular movements, parafunction, fatigue behavior, or long-term hydrolytic degradation of the adhesive interface. Second, although the 1.1-mm posts showed higher fracture resistance, remaining dentin thickness was not quantified using micro-CT and stress distribution was not evaluated using finite element analysis. Therefore, this finding should be interpreted only within the conservative, anatomy-preserving post diameters tested in this study and should not be generalized to aggressive canal enlargement. Third, two commercially available post systems were used to represent glass-fiber and quartz-fiber posts. Although post length and diameter were standardized, differences in geometry, taper, fiber arrangement, matrix composition, and manufacturer-specific design may have influenced the results; therefore, the observed differences should be interpreted as post-system effects rather than fiber-composition effects alone. Fourth, the use of monolithic 5Y-PSZ zirconia crowns, one resin cement protocol, and laboratory-based failure classification may limit direct extrapolation to other restorative materials, cementation protocols, crown designs, or clinical restorability. Finally, formal inter-examiner agreement for failure-mode classification was not assessed, although predefined categories and blinded assessment were used to reduce classification bias. Future studies should include cyclic fatigue loading, longer-term aging, micro-CT assessment, finite element analysis, matched or custom-fabricated post systems, and clinical follow-up.

The present investigation was designed to improve internal validity through standardization of ferrule, periodontal ligament simulation, crown geometry, zirconia restoration parameters, thermal aging, and loading angle. These controls strengthen comparisons among groups but also introduce limitations inherent to in vitro testing. Static loading to failure does not replicate the complex cyclic and multidirectional forces encountered clinically, particularly under parafunctional conditions. In addition, although thermal aging was performed, long-term hydrolytic degradation of the adhesive interface and fatigue-related crack propagation were not fully reproduced. The use of extracted teeth improves biologic relevance, but residual anatomical variability cannot be entirely eliminated despite dimensional screening and randomization.

Future studies should incorporate cyclic fatigue loading, longer-term aging protocols, and interface-level analyses (for example, micro-CT void assessment or fractographic evaluation) to clarify the mechanisms underlying the observed main effects. It would also be valuable to evaluate whether these findings persist under reduced ferrule conditions, different cements/adhesive strategies, or alternative crown materials, as these factors commonly vary in clinical practice. Moreover, clinical studies are ultimately needed to determine whether the laboratory gains in fracture resistance and favorable failure modes translate into improved survival and reparability in patients.

Overall, the findings support a conservative but optimized restorative approach for endodontically treated maxillary lateral incisors: when anatomy permits and apical seal is preserved, using a longer post, selecting a 1.1 mm diameter within dentin-preserving limits, choosing the tested quartz-fiber post system, and applying airborne-particle abrasion with silane may improve fracture resistance without evidence of adverse interaction among these variables. These results may help clinicians make more predictable post-selection decisions in a tooth type where structural limitations and esthetic demands frequently compete.

Conclusions

Within the limitations of this static in vitro study, fiber post length, diameter, post material/system, and surface treatment significantly affected the fracture resistance of endodontically treated maxillary lateral incisors restored with composite cores and monolithic 5Y-PSZ zirconia crowns, whereas no significant interaction effects were detected. Longer posts, 1.1-mm diameter posts within anatomy-preserving limits, the tested quartz-fiber post system, and airborne-particle abrasion followed by silanization were associated with higher fracture resistance under the specific experimental conditions used in this study.

Clinical recommendations

The present findings should be interpreted cautiously and should not be considered direct clinical recommendations, as only one crown material, one resin cement protocol, and one thermal aging protocol were evaluated, and cyclic fatigue loading was not performed. Clinically, post selection in maxillary lateral incisors should remain conservative and guided primarily by preservation of radicular dentin, maintenance of an adequate apical seal, and careful assessment of canal anatomy. Further studies using cyclic fatigue loading, longer-term aging, different restorative materials, different cementation protocols, and clinical follow-up are required to confirm the clinical relevance of these findings.

Abbreviations

APA	Airborne-particle abrasion
CEJ	Cementoenamel junction
CI	Confidence interval
EDTA	Ethylenediaminetetraacetic acid
NaOCl	Sodium hypochlorite
PDL	Periodontal ligament
SD	Standard deviation
5Y-PSZ	5 mol% yttria-stabilized partially stabilized zirconia

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Authors' contributions
MRas, MS, RF, and MR conceptualized the study and contributed to the study design. MS, DE, RT, MF, AN, HA, AE, EAG, AM, SM, EF, RF, and MR contributed to the methodology, specimen preparation, data collection, and laboratory procedures. RF and AM supervised the endodontic procedures. MRas, MS, SM, EF, and MR supervised the prosthodontic procedures and contributed to the interpretation of the findings. MS, DE, RT, MF, AN, HA, AE, EAG, AM, SM, EF, RF, and MR contributed to data analysis, manuscript drafting, and critical revision. MRas, MS, and MR performed the final revision of the manuscript. All authors read and approved the final manuscript and agree to be accountable for all aspects of the work.

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Data availability
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Ethical approval was obtained from the Institutional Review Board, Faculty of Oral and Dental Medicine, Misr University for Science and Technology, Egypt (IRB #44-11-25-1). Extracted maxillary lateral incisors were collected during periodontal surgeries after informed patient consent, and all specimens were anonymized and coded. All methods were performed in accordance with IRB requirements and applicable institutional and national guidelines, and in compliance with the Declaration of Helsinki.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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