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RESEARCH AND EDUCATION

Fatigue and failure analysis of restored endodontically treated maxillary incisors without a dowel or ferrule

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ABSTRACT

Statement of problem. Information on the survival and mode of failure of endodontically treated incisors without a ferrule and restored without dowels is lacking.

Purpose. The purpose of this in vitro study was to compare the survival and failure mode of endodontically treated incisors without a ferrule and restored with bonded ceramic crowns and various composite resin foundation restorations without dowels with a control group with fiber dowels.

Material and methods. Forty-five decoronated endodontically treated bovine incisors without ferrule were divided into 3 experimental groups and restored with different adhesive foundation restorations without dowel: nanohybrid composite resin (Nd), bulk-fill composite resin foundation restoration (NdB), and fiber-reinforced bulk-fill composite resin (NdFR). A control group with conventional foundation restorations (glass-fiber dowel with nanohybrid composite resin foundation restoration without ferrule) (D) was included for comparison. All teeth were prepared to receive bonded lithium disilicate ceramic crowns luted with dual-polymerizing composite resin cement and were subjected to accelerated fatigue testing. Cyclic isometric loading was applied to the incisal edge at an angle of 30 degrees and a frequency of 5 Hz, beginning with a load of 100 N (5000 cycles). A 100-N load increase was applied each 15 000 cycles. Specimens were loaded until failure or to a maximum for cycles endured of 1000 N (140 000 cycles). Groups were compared by using the Kaplan-Meier survival analysis (log rank test at α=.05 and pairwise post hoc comparisons) and life table analysis for load-at-failure (followed by Wilcoxon pairwise comparison α=.05).

Results. All the specimens failed before 140 000 load cycles. Even though no statistically significant differences were found between the experimental groups without dowel (P>.127), the fiber-reinforced foundation restoration yielded the highest mean ±standard deviation cycles to failure (46 023 ±4326) compared with Nd (38 899 ±2975) and NdB (39 751 ±2998). NdFR, however, outperformed the foundation restoration with glass-fiber dowel (35 026 ±2687) (P<.05). Most failure in groups without dowel were restorable, while 100% of catastrophic failure (unrestorable) were found in the group with dowels.

Conclusions. Based on the present in vitro study, dowels did not improve the performance of the adhesive restoration of endodontically treated incisors without a ferrule. The use of a short fiber-reinforced composite resin foundation restoration without a dowel was able to not only improve the resistance of the restorations compared with adhesive foundation restorations with dowels but also minimize catastrophic failures. (J Prosthet Dent 2021;■:■-■)

The restoration of endodontically treated incisors (ETIs) is still a challenge for the restorative dentist. The presence of a ferrule is paramount to the fracture resistance of ETIs[1-6]; however, the amount of remaining coronal structure is not always under the dentist's control, and a complete absence of coronal structure because of caries or previous restorations is not uncommon. Traditionally, intraradicular dowels with various foundation restoration techniques have been used to restore ETIs without a ferrule.[7,8] Recently, clinicians have become more inclined to use adhesive techniques for dowel placement and foundation restorations, as prefabricated glass-fiber dowels have become more popular than cast dowel-and-core foundation restorations.[9,10]

Glass-fiber (GF) dowels present improved esthetics and better mechanical properties (elastic modulus similar

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Clinical Implications

Badly damaged endodontically treated incisors without a ferrule perform similarly with various foundation restoration materials (with and without dowels), but it appears difficult to justify the risks associated with dowel placement (perforation, root fracture). Avoiding dowels may also favor repairable failures and prevent tooth extraction.

to that of dentin[11-13]) than cast dowel-and-core foundation restorations.[14] However, a recent meta-analysis of clinical studies reported no significant differences in the incidence of root fracture between cast dowel-and-core and GF dowel restored teeth.[10] In fact, GF dowels induced a higher incidence of catastrophic failures, conflicting with the conclusions of other reviews.[15-20] Some clinical studies have reported no improvement in survival with the use of dowels,[21-23] while others have reported better survival associated with dowel placement.[8,24,25] Thus, there is still no consensus on whether the use of a GF dowel can prevent catastrophic failures or improve the performance of ETIs.

In vitro studies have reported that the use of dowels did not enhance the fatigue resistance of posterior teeth[26-28] or anterior teeth with a ferrule.[1,29] For anterior teeth with a ferrule, more favorable failure modes were found when dowels were not present, as their placement systematically resulted in vertical root fractures.[20] In contrast, randomized clinical trials reported better survival rates of endodontically treated posterior teeth restored with dowels.[24,25] The lack of consistency in the literature on the influence of dowels in ETIs without a ferrule led to the investigation of approaches without dowels as a biomimetic (more tooth-like) alternative.

The selection of the foundation restoration material is an important factor that could also influence the outcome.[30,31] Recently, so-called bulk-fill composite resins have been introduced as an alternative to layered composite resins.[32,33] Traditionally, layered composite resin could be replaced by a single 4- to 5-mm-thick increment of bulk-fill material light-polymerized in 1 step with minimal shrinkage.[34,35] In addition to the reduced clinical time, bulk placement can help prevent the incorporation of voids and interlayer gaps, resulting in a more homogenous restoration.[36] Recent studies have reported similar mechanical performance in bulk-fill and nanohybrid composite resins.[30,33,37,38]

The incorporation of short fibers has led to improved mechanical properties of resin-based dental materials,[39,40] with recent studies revealing promising results for these fiber-reinforced composite resins (FRCRs).[37,41-48] FRCRs have the potential to stop crack propagation and act as a load-bearing barrier under high occlusal forces.[37] Promising results have recently been reported for the use of FRCRs in endodontically treated posterior teeth.[45,49-52] However, the authors are unaware of studies on their use as a foundation restoration material to restore badly damaged ETIs.

Adhesive approaches without a dowel in combination with enhanced foundation restoration materials could increase the fatigue resistance of ETIs and provide more favorable failure modes.[53] The aim of the study was to investigate the fatigue resistance and failure mode of badly damaged ETIs without a ferrule restored without a dowel and with foundation restorations made of 3 different materials: a nanohybrid, a bulk-fill, and a short-fiber-reinforced bulk-fill composite resin. The null hypotheses were that the foundation restoration material would not influence the fatigue resistance and failure mode and that the use of a dowel would be similarly ineffective in improving the performance of ETIs without a ferrule. Hence, an additional group from a previous study with identical experimental conditions and concomitantly tested was included as a control to assess this null hypothesis.[1] This study represents the third step of a comprehensive project exploring the survival of ETIs with multiple variables (the effect of ferrule, dowel type, presence of dowel, and foundation material).[1,20]

MATERIAL AND METHODS

Forty-five bovine incisors with homogeneous root proportions and root canal dimensions were selected and kept in thymol-saturated solution (Thymol; Aqua Solutions, Inc). The crowns were removed, leaving 13 mm of root, and subsequently assigned to 3 different experimental groups without dowel (n=15) that received a foundation restoration with conventional composite resin (Miris 2; Coltène) (Nd), a foundation restoration with bulk-fill composite resin (Tetric EvoCeram Bulk Fill; Ivoclar Vivadent AG) (NdB), or a foundation restoration with short-fiber-reinforced bulk-fill composite resin (everX Posterior; GC Corp) (NdFR) as shown in Figure 1. A chemomechanical endodontic treatment was performed according to a previously published protocol including the placement of a 1-mm thick glass ionomer barrier.[20] Then, acrylic resin (Palapress Vario; Kulzer GmbH) was used to embed 10.5 mm of the root.

For all groups, a severely damaged incisor was simulated by reducing the thickness of radicular dentin through a box preparation (Fig. 2), leaving a 1.5-mm-thick circumferential dentin wall, according to a previously published protocol.[20] The prepared tooth surfaces were airborne-particle abraded with 27-μm-silica-coated Al_2O_3 powder (CoJet; 3M ESPE). Then, the dentin was etched with 35% phosphoric acid (Ultra-Etch; Ultradent Products, Inc) for 10 seconds, rinsed, and gently dried, followed by application of the primer (20 seconds) and adhesive resin (20 seconds) (OptiBond FL; Kerr Corp).

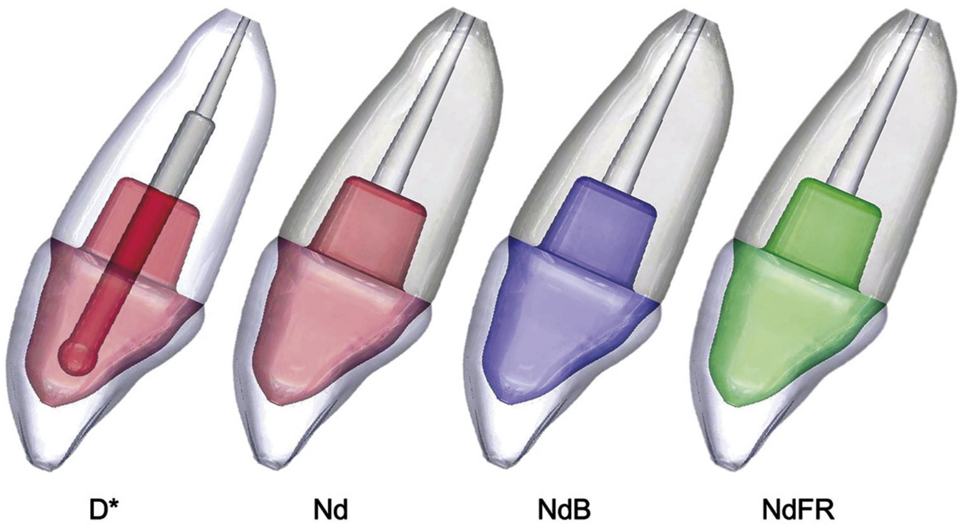

Figure 1. Experimental groups with different restorative materials: D, fiber dowel and composite resin (*red*). Nd, without-dowel and composite resin (*red*); NdB, without-dowel and bulk fill composite resin (*purple*); NdFR, without-dowel and fiber-reinforced bulk fill composite resin (*green*). *Additional group tested under identical experimental condition by same operators in previously published data.

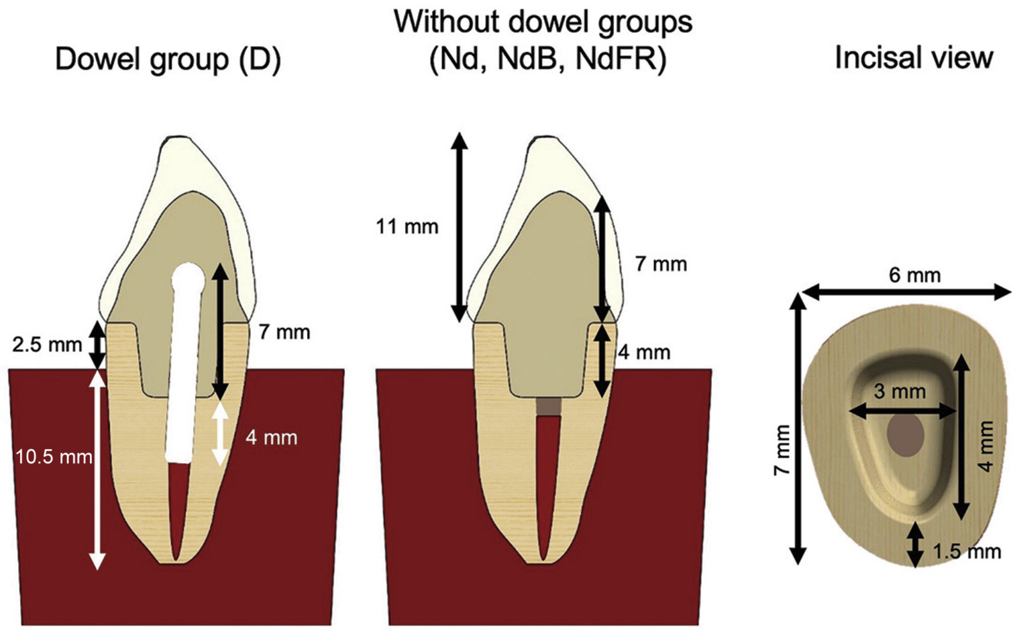

Figure 2. Dimensions of specimens in occlusal and proximal views.

Three different composite resins were used for the foundation restoration: Miris 2, Tetric EvoCeram Bulk Fill, and everX Posterior. The specifications of the composite resins are presented in Table 1. To build the 11-mm-high foundation restoration (4 mm below and 7 mm above the cervical preparation), 5 increments were used for Miris 2, each increment polymerized at 1000 mW/cm^2 (VALO; Ultradent Products, Inc) for 20 seconds. For Tetric EvoCeram Bulk Fill and everX Posterior, only 2 increments were used. Finally, they were polymerized for 10 seconds with a glycerin barrier (KY Jelly; Johnson & Johnson Inc) applied to avoid the oxygen-inhibited layer (Fig. 3). The lithium disilicate ceramic crowns (IPS e.max CAD; Ivoclar Vivadent AG) were milled to standard dimensions (11 mm height and 9 mm proximal width) (Fig. 4). The crown fabrication, preparation cleaning, and crown luting were performed according to a previously published protocol.[20] Before the accelerated fatigue testing, all specimens were stored in distilled water at room temperature (24 °C) for a minimum of 24 hours.

Table 1. Foundation restoration materials and manufacturer information

Parameter	Miris 2	Tetric EvoCeram BulkFill	everX Posterior
Manufacturer	Coltène	Ivoclar Vivadent AG	GC Corp
Description	Light-polymerized, nanohybrid conventionally layered composite resin.	Light-polymerized, nanohybrid bulk fill composite resin.	Light-polymerized, short-fiber-reinforced bulk fill composite resin
Matrix	Bis-GMA, TEGDMA, UDMA	Bis-GMA, Bis-EMA, UDMA	Bis-GMA, TEGDMA, PMMA
Filler	Silanized barium glass, amorphous silica.	Barium glass, ytterbium trifluoride, mixed oxides	E-glass fiber and barium borosilicate glass filler
Filler content (weight%)	80	62.5	77
Flexural strength (MPa)	120	120	124
Fracture toughness, Kmax value	np	2.2	5.1
Modulus of elasticity (GPa)	13	10	9.5

np, not provided by manufacturer.

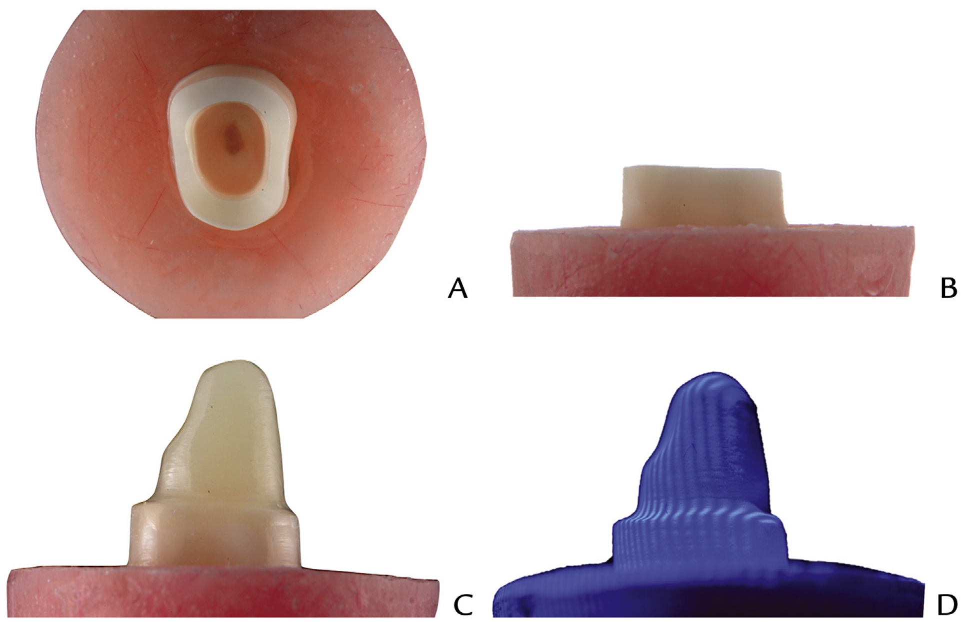

Figure 3. A, Occlusal views of embedded root after endodontic treatment and glass ionomer barrier. B, Proximal view after endodontic treatment and glass ionomer barrier. C, Proximal view of finished tooth preparation without dowel and without ferrule. D, Digital scanning of tooth preparation.

Mastication was simulated by using a closed-loop electrodynamic system (Acumen III; MTS Systems). An isometric contraction (load control) was applied through a flat composite resin antagonist (Z100; 3M ESPE) at a lingual angle of 30 degrees (Fig. 5A) and contacting three-fourth of the flat incisal edge (Fig. 5B), while the specimens were submerged in distilled water. Cyclic load was applied (5 Hz), initially with a 100-N load (warmup of 5000 cycles), followed by a 100-N increase every 15 000 cycles up to 1000 N. The specimens were loaded until fracture or to a maximum of 140 000 cycles.

A macrovideo camera (Vixia HF S100; Canon) was used to continuously record the test and detect any premature failure (Fig. 5C). The number of endured cycles, load at failure, and failure mode of each specimen were recorded. After the test, each specimen was transilluminated (Microlux; Addent) and evaluated with an optical microscope (Leica MZ 125; Leica Microsystems) at ×10 magnification. Fracture mode was categorized as repairable fracture, possibly repairable, and catastrophic, as shown in Figure 6.

The Kaplan-Meier test was applied to compare the fatigue resistance of the groups regarding the cycles (continuous variable). The effect of the foundation restoration material and the use of dowels were assessed by the post hoc log-rank test. Life table analysis was applied to compare the fracture load step at which the specimen failed (ordinal variable), followed by the Wilcoxon test (α=.05 for all statistical analyses). The data were analyzed with a statistical software program (IBM SPSS Statistics, v23; IBM Corp).

A previously published control group (D), created and tested at the same time by the same authors, was added for comparison. The previous data included 1 group with a glass-fiber dowel and nanohybrid composite resin for the core-foundation restoration (D).[1,20] The present study was a subset of a comprehensive experiment sharing the control groups.

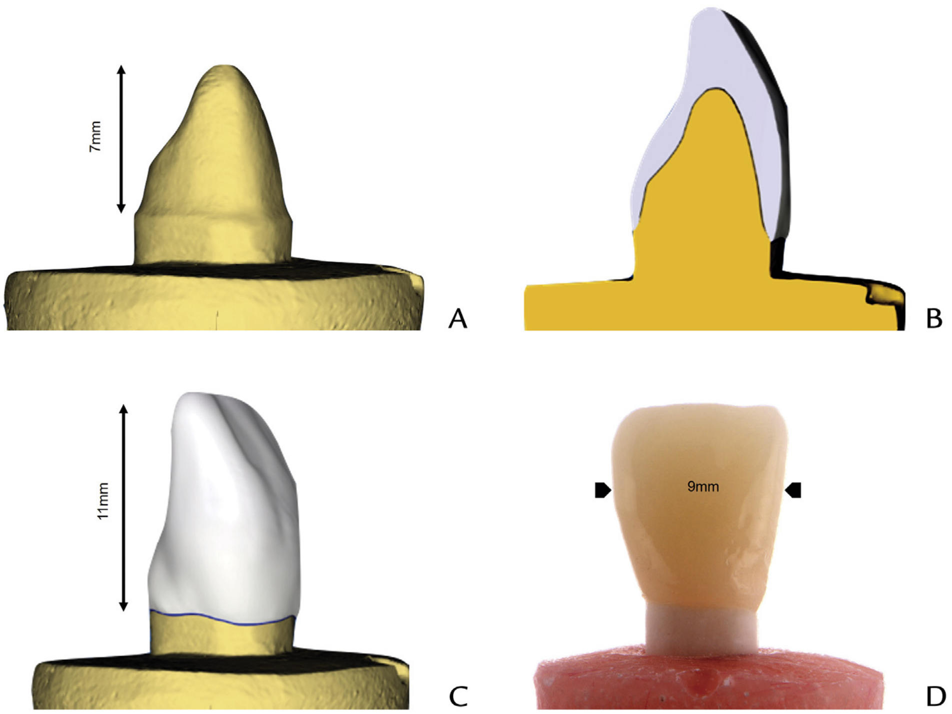

Figure 4. A, Proximal view of digitized preparation in CAD-CAM software program. Note chamfer preparation because of immediate dentin sealing technique in shoulder area. B, Buccolingual cross-sectional view of preparation and crown. C, Height of crown. D, Width of bonded crown before fatigue test. CAD-CAM, computer-aided design and computer-aided manufacture.

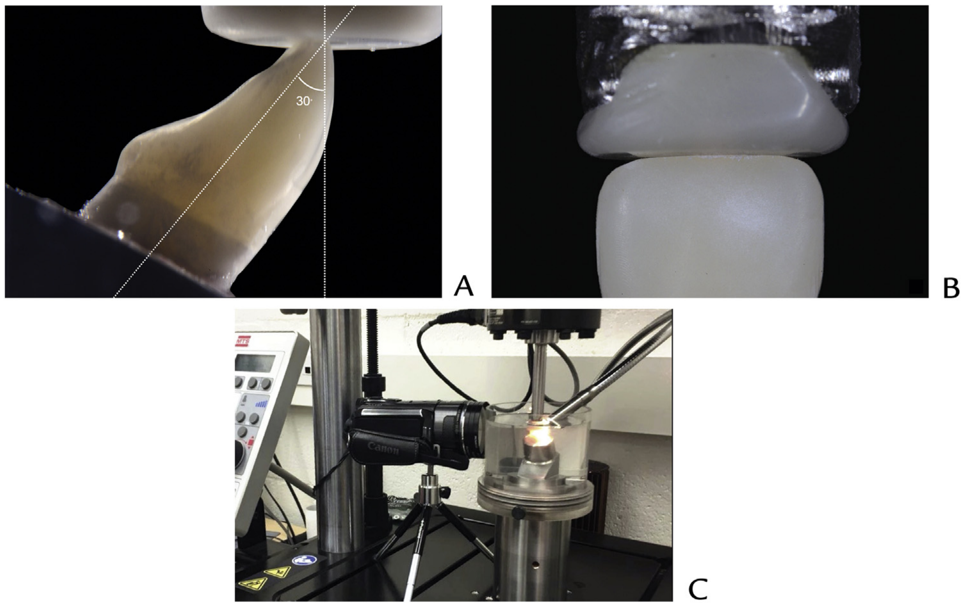

Figure 5. A, Specimen loaded at 30 degrees submerged in distilled water. B, Flat composite resin used as antagonist. C, Specimens transilluminated and tests filmed with macrovideo camera.

RESULTS

All specimens failed before the end of the test (140 000 cycles). In the previous study, the failures of all 15 specimens with glass-fiber dowel (group D) were preceded by the failure of the lingual margin (initial failure), resulting in the cyclic opening of a wide gap between the foundation restoration and crown assembly and the root (Fig. 7 and Video 1). For group D, the number of cycles until the opening of the lingual margin was computed for fatigue resistance and load at failure. As all the specimens

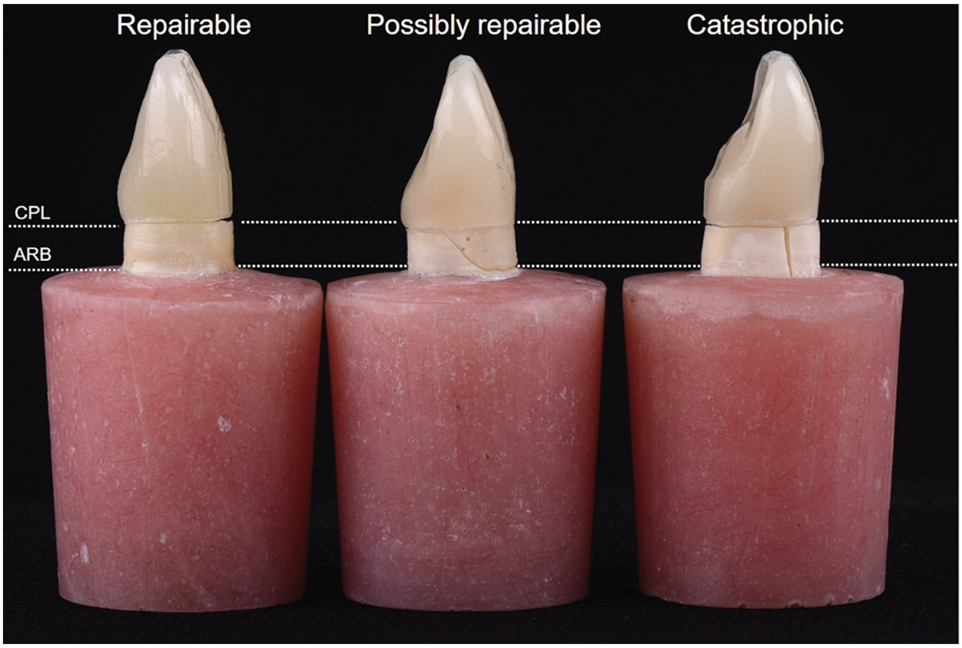

Figure 6. Failure mode: repairable failure, cohesive fracture of foundation restoration or crown above cervical preparation limit (CPL); possibly repairable failure, restricted root fracture between CPL and acrylic resin base (ARB); catastrophic failure, longitudinal root fracture that propagates below ARB (root extraction would be necessary, clinically).

failed, the mean cycles and median load at failure could be obtained (Figs. 8 and 9, Table 2). The fatigue resistance survival curves are presented for all 60 specimens considering cycles (Fig. 8A) and load (Fig. 9A).

The Kaplan-Meier and post hoc log rank test for the number of cycles to failure revealed significantly higher mean ±standard error survival for the group with fiber-reinforced composite resin core foundation restorations without dowel (NdFR: 46 023±4326) than initial failure in the group with dowel (D: 35 026 ±2687). No difference was found within the 3 groups without a dowel for either cycles or load (Table 2). Life table followed by the post hoc Wilcoxon test for the mean load at failure revealed significantly higher loads for NdFR (492 N) than for D (425 N) (P=.049). The median load at failure for Nd and NdB was 450 N for both groups, with no statistically significant difference to NdFR or D (Table 2). The descriptive statistics of the data are shown in a box and whisker diagram in Figure 9B. All specimens with dowels (D) fractured catastrophically (100%), while groups without dowels presented 60% or more noncatastrophic failures, as shown in Figure 10.

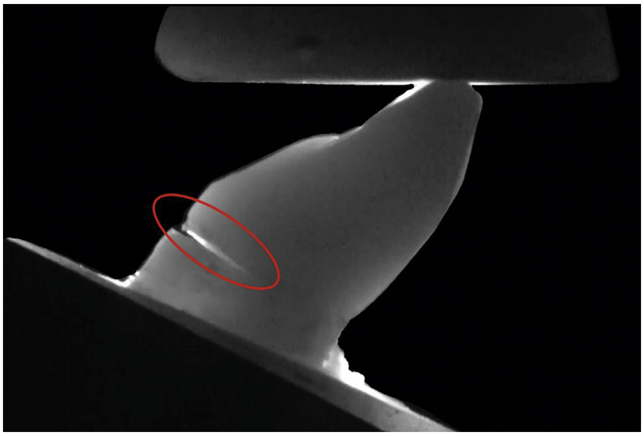

Figure 7. Premature failure (initial failure) of specimen characterized by cyclic opening of wide gap at lingual margin between foundation restoration or crown assembly and root. Although clinical detection of such failures appears questionable, occurrence of premature cracks and root fractures justified analysis of survival to be conducted for “initial failure” in group with dowel (group D). Such occurrence not found in groups without dowel.

DISCUSSION

This study investigates the mechanical behavior of ETI without ferrule restored with ceramic crowns bonded to different foundation restorations without dowels in comparison with a group with dowels. The first null hypothesis was not rejected because the buildup material did not influence the fatigue resistance among the groups without a dowel. The second null hypothesis was rejected because the use of a dowel adversely affected the fatigue resistance and failure mode of the restored teeth.

As direct adhesive restorations reinforce the weakened tooth,[5] the mechanical and physical properties of direct restorative materials should be considered to optimize the performance of the restoration-root complex. As seen in Table 1, the mechanical properties of the

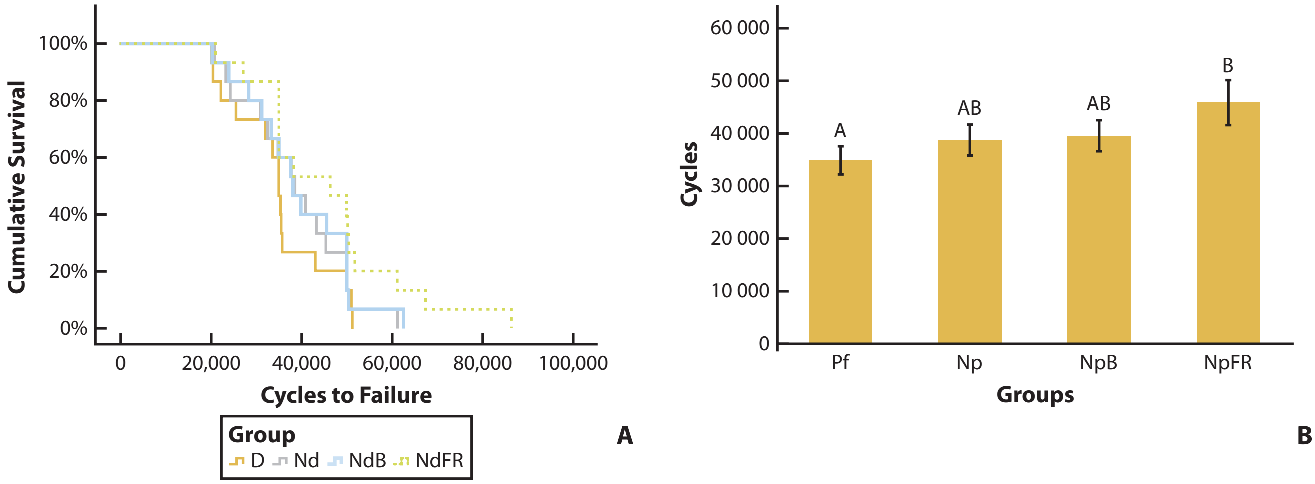

Figure 8. A, Kaplan Meier fatigue resistance survival curves (cycles) for all four groups — for better understanding and comparison, D group from previous study was included (strictly identical experimental condition and concomitantly tested). B, Mean survived cycles and standard errors. Kaplan-Meier and log rank post hoc test. Different letters indicate significant differences ($P<.05$). D, with glass-fiber dowel; Nd, without dowel with composite resin foundation restoration; NdB, without dowel, with bulk-fill composite resin foundation restoration; NdFR, without dowel, with fiber-reinforced composite resin foundation restoration.

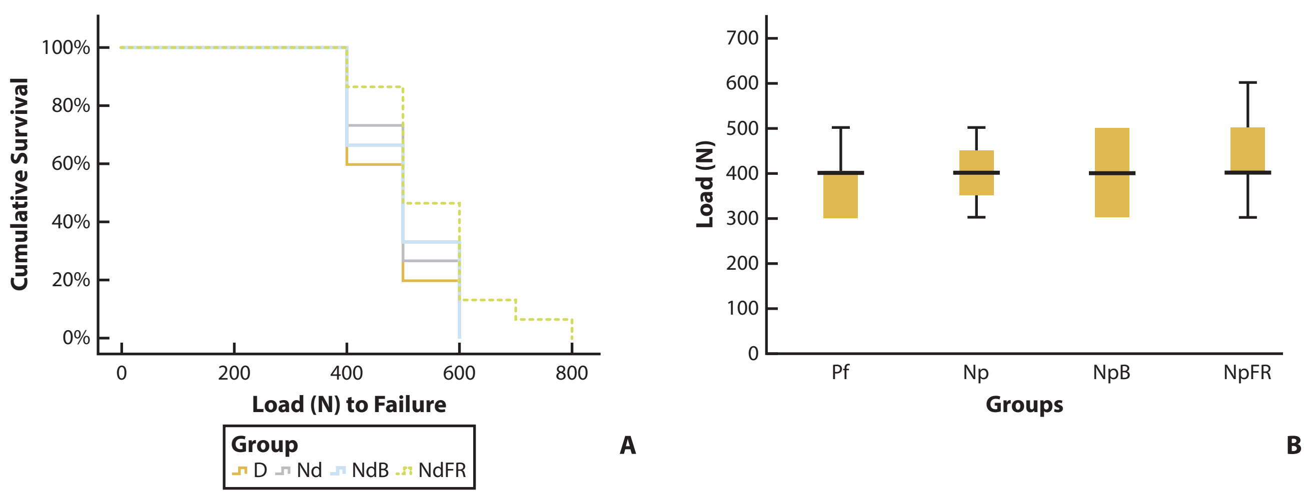

Figure 9. A, Life table curves of survived loads for all groups. B, Box-and-whisker diagram of fracture loads presenting median (*bold black horizontal line*), minimum and maximum values (vertical "t" lines, or whiskers), total number of specimens (N=60, n=15), and interquartile range (*box*). D, glass-fiber dowel with composite resin foundation restoration; Nd, without dowel with composite resin foundation restoration; NdB, without dowel with bulk-fill composite resin foundation restoration; NdFR, without dowel with fiber-reinforced composite resin foundation restoration.

3 composite resins were similar, although the FRCR had a higher fracture toughness, which could significantly improve the mechanical behavior of the foundation restoration with increased crack-deflection ability.[44] In the present study, however, no statistically significant difference was found in the fatigue resistance among the 3 different foundation restoration materials in the groups without dowels. Atalay et al[30] evaluated nanohybrid (Tetric N-Ceram; Ivoclar Vivadent AG), bulk-fill (Filtek Bulk Fill Posterior Restorative; 3M ESPE), and fiber-reinforced (everX Posterior; GC Corporation) composite resins for mesial-occlusal-distal (MOD) restorations on endodontically treated premolars and reported no difference among those materials in a single load-to-failure

Table 2. Pairwise post hoc comparison

Group	D	Nd	NdB	NdFR
D	-	.429	.388	.036*
Nd	.463	-	.926	.127
NdB	.508	1.000	-	.136
NdFR	.049*	.165	.190	-

B, bulk-fill composite resin; D, glass-fiber dowel; FR, fiber-reinforced composite resin; Nd, without dowel. Shaded cells, Kaplan-Meier followed by post hoc log rank tests for cycles; clear cells, life table followed by post hoc Wilcoxon-Gehan test for load. *Statistically significant difference between groups ($P<.05$).

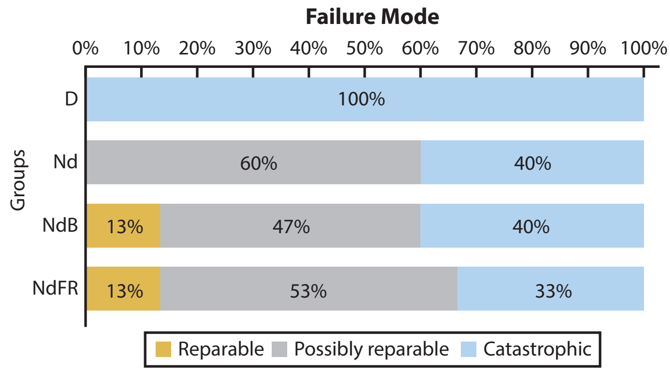

Figure 10. Percentage of specimens per group for each failure mode category. D, glass-fiber dowel with composite resin foundation restoration; Nd, without dowel with composite resin foundation restoration; NdB, without dowel with bulk-fill composite resin foundation restoration; NdFR, without dowel with fiber-reinforced composite resin foundation restoration.

test. However, data regarding bulk fill and/or FRCR used for foundation restorations without a dowel of ETI are lacking.

Although the mean fracture loads and survived cycles were statistically similar among the groups without a dowel, the group NdFR showed a superior survival (cycles endured) in comparison with the group with a dowel (D). Thus, the combination of the without-dowel approach with short-fiber-reinforced composite resin appears to be a promising option. Frater et al[45] reported the superior strength, failure mode, and interfacial adaptation of FRCR foundation restorations without a dowel. Similarly, in the present study, FRCR presented better fatigue resistance (P=.036) and failure mode than the dowel group (D). The mechanical properties of everX Posterior and those of the conventional restorative composite resin,[43] however, were similar in the absence of a dowel. Using a dowel with everX Posterior was not tested because of the geometric and technical limitations of the fibers (difficulty to pack and adapt the composite resin around the dowel in an incisor).

Recent studies with posterior teeth[27,31] have reported that bonding to the coronal root dentin and internal walls of the pulp chamber dentin provides adequate retention without dowels, which have been associated with increased catastrophic failures.[27,29] These findings were consistent with those of the present study because no difference was observed between groups with (D) or without dowel (Nd/NdB). The lack of effect of the dowel is evident between the groups made with Miris 2 as a core buildup material (D and Nd). However, additional computations were carried out comparing the bulk-fill groups (without dowel group from this study, NdB, and group with dowel from previously published data, D).[20] Using bulk-fill material as a foundation yielded the same survival results as Miris 2, further confirming that adding a glass-fiber dowel not only fails to strengthen the assembly but also results in 100% catastrophic failures.

The glass-fiber-reinforced dowel has been reported to prevent catastrophic root fractures because of its properties similar to those of dentin.[11-13] However, the present study did not support that finding as groups without dowel presented less than 40% of catastrophic failures.

The initial failure, cyclic opening of the lingual margin between the root and crown-foundation restoration assembly, was always associated with the presence of a dowel (group D and all dowel groups in previously published study[20]) and never occurred in groups without dowel. This phenomenon has been previously reported, including in load-to-failure tests,[54,55] in a literature review,[6] and in accelerated fatigue studies in molars[27,31] and anterior teeth with a ferrule.[1] This type of failure could only be detected with the live video recording and transillumination, as previously suggested by the authors (Video 1).[1,20] The critical stage of initial failure was used for comparisons because it is the starting point of fractures propagating by cyclic fatigue (gap opening).[1,20] This phenomenon (initial failure) led to rejection of the second null hypothesis because the use of a dowel negatively affected the fatigue resistance when compared to NdFR. Groups with dowels were affected by a premature failure that was computed for comparison.[1,20]

Overall, it appears that the use of a dowel is not necessarily beneficial and should be questioned even in extensively damaged ETIs. Initial failures of foundation restorations with dowels, such as cyclic opening, infiltration gap, and bacterial leakage, are typically undiagnosed and unnoticed by the patient, progressing to mobility or total fracture of the restoration. On the other hand, restorations without dowel typically fail without initial failure (patient will likely consult immediately) and most likely are restorable (Fig. 10).

The present study was not consistent with a randomized clinical trial by Ferrari et al,[25] who reported better clinical survival and success rates for endodontically treated premolars restored with dowels than for restorations without dowels over a 6-year period. Similarly, another clinical study[24] reported better survival and success rates for single-rooted and multirooted teeth restored with dowels than for restorations without dowels over a period of at least 5 years. Both studies, however, used different materials and delivery approaches compared with the present study (nonadhesive metal-ceramic complete crowns). This may explain the different results of the present study, as bondable glass-ceramic restorations are less likely to induce stress concentration than metal-ceramic crowns.[56]

Limitations of the present study included the use of bovine teeth instead of human teeth, the fact that only mechanical aging was simulated (no thermocycling or bacterial challenges), and the difficulty in correlating the in vitro number of cycles and load with the in vivo service time and masticatory activity. Thus, randomized clinical trials with approaches without dowel on ETI restored with bonded restoration should be performed based on the materials, techniques, and outcomes of the present in vitro study.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. All buildup approaches without a dowel had similar performance, however, the no-dowel short-fiber reinforced buildup outperformed the classic approach with a glass-fiber dowel.
2. The use of a glass-fiber dowel did not enhance the survival of the ETI restored with bonded lithium disilicate crowns over composite resin foundation restoration.
3. Less catastrophic failures were found in composite resin foundation restorations without dowels, while the use of dowels was associated with 100% catastrophic root fractures without improvement in endured cycles.

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