

Accelerated fatigue resistance of endodontically treated incisors without ferrule restored with CAD/CAM endocrowns

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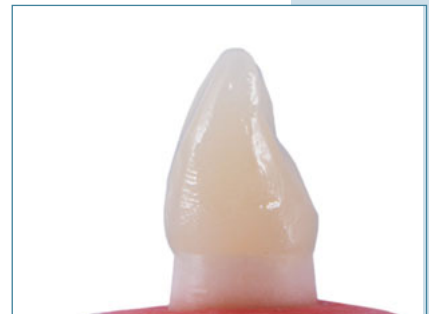
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Abstract

Purpose: The present study aimed to investigate the resistance and failure mode of broken-down endodontically treated incisors without ferrule restored with CAD/CAM endocrowns.

Materials and methods: Endodontically treated bovine incisors ($N = 30$) without ferrule were divided into two groups and restored with two types of CAD/CAM endocrowns: lithium disilicate (Eld) or resin nanoceramics (Erc). The preparations included a 4-mm-deep 'internal ferrule' and immediate dentin sealing. The samples were subjected to accelerated fatigue testing. Cyclic isometric loading was applied to the incisal edge at a 30-degree angle at a frequency of 5 Hz, beginning with a load of 100 N (5,000 cycles). A 100 N load increase was applied every 15,000 cycles. Specimens were loaded until failure or to a maximum of 140,000 cycles. Previously published data from the same authors regarding lithium disilicate crowns over post-and-core buildups without ferrule (NfPf), core buildups without post without ferrule (NfNpFR), and with a 2-mm ferrule (FNp) using the same experimental setup were included for comparison. Groups were compared using the Kaplan Meier survival analysis for cycles (log rank pairwise post hoc test comparisons

at $P = 0.05$) and Life Table survival analysis for load at failure, followed by the Wilcoxon pairwise comparison at $P = 0.05$.

Results: All specimens failed before 140,000 load cycles. There was no statistically significant difference between the endocrown materials (Eld: 53,448 mean endured cycles; Erc: 52,397 mean endured cycles; $P = 0.844$). Endocrowns outperformed the group with lithium disilicate crowns on incisors without ferrule and post-and-core buildup (NfPf with mean endured 35,025 cycles), showed no statistical difference compared with the group with no-post fiber-reinforced composite resin core buildup (NfNpFR with 45,557 mean endured cycles), and had a lower survival rate compared with the group with ferrule (FNp with mean endured 73,244 cycles). Endocrowns generated a majority of non-catastrophic failures (with an advantage for Erc), while 100% of catastrophic failures were found in the group with a post.

Conclusions: CAD/CAM endocrowns of nonvital incisors without ferrule improved the resistance and optimized the failure mode when compared with traditional bonded crowns with adhesive post-and-core and no-post buildups.

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Introduction

The rehabilitation of severely broken-down endodontically treated teeth (ETT) without coronal tooth structure is still a challenge in modern dentistry and involves a variety of treatment options.^{1,2} Despite the fact that restorative treatment is critical to the long-term success of endodontic treatment, the possible reconstruction materials and techniques are still being debated, especially for the anterior dentition. Traditionally, anterior teeth with extensive coronal loss have been restored with full crowns cemented over cast post-and-core buildups (retention and resistance form) or direct post-and-core buildups (adhesion form).

It has been proven that the main role of a post in the retention of the core is not as relevant for posterior teeth, where masticatory loads are essentially compressive vertically.^{1,3} On the other hand, as maxillary incisors are loaded obliquely, the influence of a post on the flexural behavior of a tooth should be considered in order to reduce tooth fracture.^{1,4} Controversy exists regarding the biomechanical requirement of the macro-mechanical retention provided by posts in both *in vivo* and *in vitro* investigations,⁵⁻¹⁸ with many associated complications, especially the high stress concentration on the root, leading to unfavorable root fractures.^{14,17,19-21}

Recent studies have shown that the placement of a post causes a large number of catastrophic failures, even among restorations with adhesive post-and-core buildups.^{14,17,20} A no-post alternative to treat ETT involves the use of the pulp chamber and/or coronal part of the endodontic canal as an adhesive surface for a bonded endocrown. This technique is a significant simplification, with both the crown and the core buildup being a single unit. Endocrowns are retained mainly by micro-retention through the use of adhesive cementation and also in part by macromechanical retention provided by

the pulpal walls. Compared with traditional crowns with posts and cores, which require many steps to perform, the endocrown has many practical advantages: it is easy to perform, simpler, quicker, cheaper due to fewer steps involved, and has good esthetic acceptance.²²⁻²⁴ Moreover, endocrowns manufactured through CAD/CAM technology are straightforward to obtain.

Due to the recent increase in popularity of endocrowns, many case reports have been published describing the clinical steps for their fabrication, their enhanced *in vitro* performance,^{8-10,25} and their high success rate in posterior teeth.^{22,26-29} According to short-term clinical reports, the survival rate of endocrowns is 90% to 95% for posterior teeth.²⁹⁻³¹ Recent systematic reviews and meta-analyses evaluating clinical trials and *in vitro* studies on endocrowns suggest that they may perform similarly or better than conventional treatments using intraradicular posts, direct composite resin or inlay/onlay restorations.^{28,32,33} This technique represents a promising and conservative alternative to full crowns for the treatment of posterior nonvital teeth that require long-term stability.^{22,28,29,34} However, apart from all the research on posterior endocrowns, there are only a few finite element analyses³⁵⁻³⁸ and *in vitro* studies^{10,39} on endocrowns used in the anterior dentition. To date, no *in vitro* studies have been carried out on incisors without ferrule restored with different endocrown materials.

In addition, thanks to CAD/CAM technology, besides the traditional ceramic blocks, high-performance polymer blocks (HPP) have recently been introduced. The manufacturing of these materials under controlled industrial conditions has been shown to provide optimized mechanical properties of the resulting restoration compared with those prepared under handcrafted conditions.⁴⁰ Due to their enhanced biomimetic properties (dentin-like flexibility and enamel-like wear), composite



resin materials may also have an advantage in the monolithic restoration of broken-down endodontically treated incisors (ETIs).

The no-post adhesive endocrown approach in combination with new, enhanced HPPs could increase the fatigue resistance of no-ferrule ETIs and provide a more favorable failure mode. The aim of the present study was to investigate the fatigue resistance, load-at-failure, and failure mode of broken-down ETIs without ferrule restored either with a lithium-disilicate ceramic endocrown or with a resin nanoceramic endocrown.

The main null hypothesis in the present study was that the endocrown material would not lead to different fatigue resistance of failure mode. Additional groups with classic lithium disilicate crowns (including composite resin buildups) from previous studies with the same experimental setup were included to test two additional hypotheses:^{14, 17, 21} a group with ferrule and without post (FNp); a group without ferrule and with fiber post (NfPf); and a group without ferrule and without post (NfNpFR). The first additional null hypothesis was that the presence of ferrule would not influence the fatigue resistance and failure mode. The second additional null hypothesis was that the presence of post would not influence the fatigue resistance and failure mode in adhesively restored ETIs.

Materials and methods

Thirty identical bovine incisors with similar pulp space dimensions had the anatomical crown sectioned 13 mm from the apex. The teeth were mounted with acrylic resin (Palapress vario; Hereaus Kulzer), embedding the root up to 2.5 mm below the cervical preparation limit (CPL). The teeth were randomly distributed into two groups ($n = 15$): lithium disilicate endocrowns (Eld) and resin nanoceramic endocrowns (Erc).

Tooth preparation

In all 30 roots, a standard chemomechanical endodontic protocol with ideal irrigants was used.^{41,42} After the endodontic treatment, a so-called 'internal ferrule' was prepared using a conical-shaped bur. The internal ferrule was in the form of a box to simulate an extensively damaged ETI and had the following dimensions – depth: 4 mm from the CPL; buccolingual width: 4 mm; mesiodistal width: 3 mm, which left a 1.5-mm-thick residual dentinal wall (Figs 1 and 2). Then, a glass-ionomer barrier (Vitrebond Plus; 3M ESPE) of a thickness of 1 to 1.5 mm was applied to the base of the box. The prepared teeth were sandblasted with 27- μ m silicated Al_2O_3 powder for cleaning purposes (CoJet; 3M ESPE). Prior to the digital impression, immediate dentin sealing (IDS) was performed for bonding optimization.^{29,43-45} The dentin was etched for 10 s with 35% phosphoric acid (Ultra-Etch; Ultradent), rinsed, and gently dried. A total-etch adhesive system was used (OptiBond FL; Kerr) with 20 s of primer application, followed by a bonding layer (no air thinning). The adhesive was polymerized at 1,000 mW/cm² (VALO Curing Light; Ultradent) for 40 s, followed by a final polymerization for 10 s with a glycerin barrier (K-Y Jelly; Johnson & Johnson) in order to limit the oxygen-inhibited layer. The final aspect of the preparation is presented in Figure 2.

Manufacturing of endocrowns

The teeth were restored using monolithic restorations obtained with the Cerec 3 (Sirona) CAD/CAM system. Following IDS, the roots were powdered for digital impression (IPS Contrast Spray Chairside; Ivoclar Vivadent) with the Cerec Bluecam IOS (Sirona). Endocrowns of standardized dimensions and anatomy (incisocervical length: 11 mm; mesiodistal width: 9 mm) were

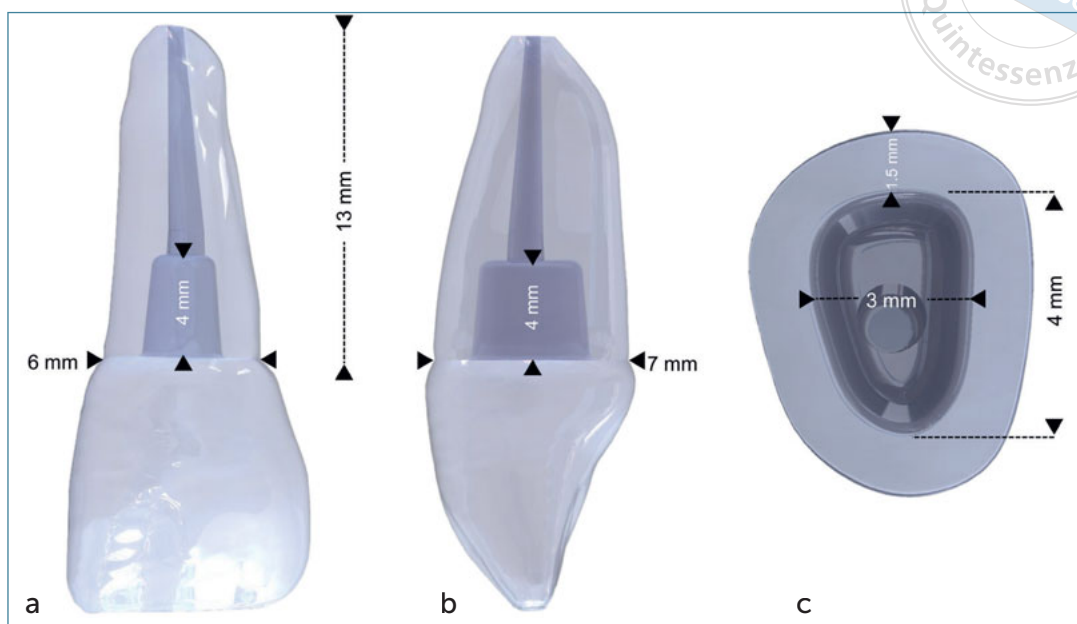


Fig 1 Detailed tridimensional representation of the samples and dimensions: buccal (a), proximal (b), and incisal (c) views. Root dimensions – length: 13 mm; mesiodistal width: 6 mm; buccolingual width: 7 mm. Internal ferrule dimensions – depth: 4 mm; mesiodistal width: 3 mm; buccolingual width: 4 mm, which left a 1.5-mm-thick dentinal wall.

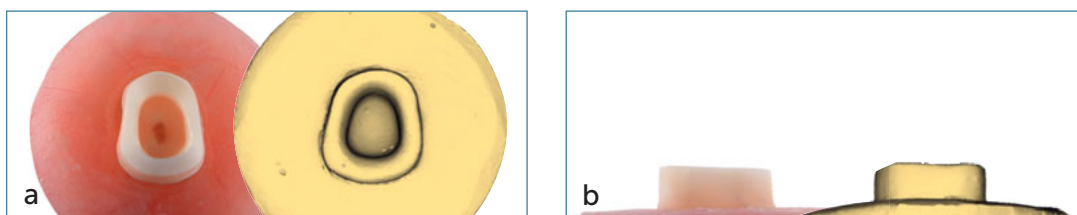


Fig 2 Preparation and corresponding CAD model for endocrown (tooth and CAD model): incisal (a) and proximal (b) views.

designed in the 4.2 Cerec software (Sirona) to fit the root preparation (Fig 3). The restorations were milled either in lithium disilicate ceramic (IPS e.max CAD; Ivoclar Vivadent) or resin nanoceramics (Lava Ultimate; 3M ESPE). Table 1 presents the mechanical properties of these materials.

After milling, the lithium disilicate restorations were glazed and crystalized according to the manufacturer's protocol (Programat CS; Ivoclar Vivadent) using IPS Object Fix Putty and IPS e.max CAD Crystal Glaze Spray (both Ivoclar Vivadent). The

resin nanoceramic restorations were polished with a coarse rubber wheel to grind off the sprue, a medium rubber wheel to finish the sprue area, a soft brush with a polishing agent (Diamond Twist SCL; Premier Dental), and a muslin rag wheel to buff the restoration.

Adhesive luting of restorations

The endocrowns were cemented with dual-cure resin cements: Variolink Esthetic DC (Ivoclar Vivadent) for the lithium disilicate

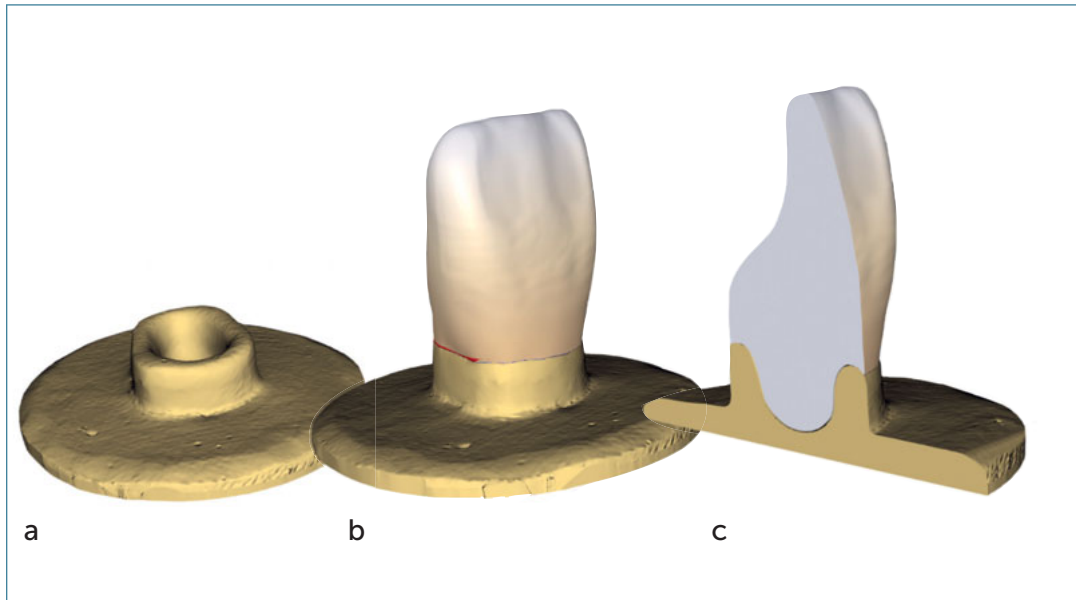


Fig 3 Restoration design steps in Cerec 4.2 software showing the endocrown root preparation (a), final endocrown restoration (b), and cross-sectional view of the endocrown and root preparation (c).

Table 1 Mechanical properties (according to manufacturers) of restoration materials used to obtain the two endocrown types

Parameter	IPS e.max CAD	Lava Ultimate
Manufacturer	Ivoclar Vivadent	3M ESPE
Description	Lithium disilicate glass-ceramic	Resin nanoceramic high-performance polymer
Flexural strength (MPa)	360 ± 60	204 ± 19
Fracture toughness, K1c (MPa m ^{1/2})	2.0 – 2.5	2.02 ± 0.15
Modulus of elasticity (GPa)	95 ± 5	12.77 ± 0.99

and RelyX Ultimate (3M ESPE) for the resin nanoceramic restorations. Before cementation, each restoration was fitted on its respective tooth to check its marginal adaptation. The fitting surface of the resin nanoceramic restorations was cleaned in an ultrasonic bath in distilled water for 1 min, air dried, sandblasted with 27- μ m silicated Al₂O₃ powder, cleaned with alcohol, and air dried. Scotchbond Universal Adhesive (3M ESPE) was applied and rubbed in for

20 s, then air thinned for 5 s. For the lithium disilicate restorations, an ultrasonic bath was also performed for cleaning, followed by etching with 5% hydrofluoric acid (IPS Ceramic Etching Gel; Ivoclar Vivadent) for 20 s, then post-etching cleaning was carried out for 1 min in distilled water, again in an ultrasonic bath. Silane for lithium disilicate (Monobond Plus; Ivoclar Vivadent) was applied with a microbrush and heat dried at 100°C for 5 min (DI-500 oven; Coltene).

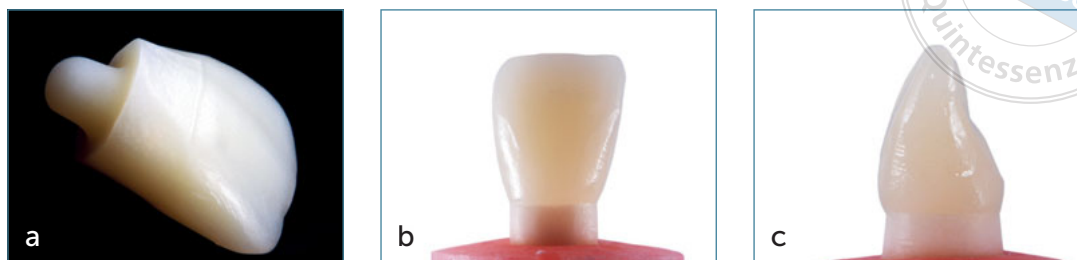


Fig 4 Resin nanoceramic endocrowns after milling showing the internal ferrule restoration extension/box (a) as well as the buccal (b) and proximal (c) views of the bonded and finished endocrown ready for the fatigue test.

The IDS layer of the prepared teeth was sandblasted with 27- μm silicated Al_2O_3 powder. The cement was applied to the inner walls of the concave internal ferrule in the root, and then the endocrown was seated on the tooth. Cement excesses were removed, followed by light polymerization three times for 20 s each on each surface (buccal and lingual) with a LED light (120 s in total). Air-blocking barrier was used to cover all the margins, and additional polymerization was carried out for 10 s per surface. The margins were finished with hand instruments (scalpel and scaler). The final restoration aspect is presented in Figure 4. The samples were stored in distilled water at room temperature (24°C) for a minimum of 24 h following adhesive restoration placement and then subjected to accelerated fatigue testing. Table 2 presents the materials used in the present study.

Accelerated fatigue procedure

Masticatory forces were simulated using a closed-loop artificial mouth electrodynamic machine (Acumen III; MTS Systems). The chewing cycle was simulated by an isometric contraction (load control) applied through a flat composite resin antagonist (Z100; 3M ESPE). The low stiffness and toothlike wear of the composite resin

flat surface provides a realistic simulation of tooth contact through a wear facet, allowing the distribution of the load without reaching the compressive limit of the restorative materials.

The force was applied at a palatal angle of 30 degrees with the flat surface contacting 3/4 of the incisal edge. The load chamber was filled with distilled water to submerge the sample during testing. Cyclic loading was applied at a frequency of 5 Hz, starting with 100 N (warm-up of 5000 cycles), followed by a 100 N increase every 15,000 cycles up to 1000 N. Samples were loaded until fracture or to a maximum of 140,000 cycles.

Analysis

To identify any premature failure, all fatigue tests were monitored using transillumination (IL-88-FOI Microscope Light Source; Scioscope) and a macro video camera (Canon Vixia HF S100; Canon) to film the entire test. The number of endured cycles, load-at-failure, and failure mode of each specimen was recorded. After the test, each sample was evaluated by transillumination (Microlux; AdDent) and optical microscope (Leica MZ 125; Leica Microsystems) at 10:1 magnification. Considering the reparability of the tooth, a visual distinction was made among

Table 2 Material application, brand name, composition, and manufacturers of the materials used in the present study

Application	Brand name	Composition	Manufacturer
Acrylic resin for tooth mounting	Palapress Vario	<i>Powder</i> : methyl methacrylate copolymer; <i>Liquid</i> : methyl methacrylate, dimethacrylate	Hereaus Kulzer, Wehrheim, Germany
Glass-ionomer barrier	Vitrebond Plus	<i>Liquid</i> : resin modified polyalkenoic acid, HEMA (2-hydroxyethylmethacrylate), water, and initiators (including camphorquinone); <i>Paste</i> : HEMA, BIS-GMA, water, initiators and a radiopaque fluoroaluminosilicate glass (FAS glass)	3M ESPE, Seefeld, Germany
Air abrasion/ silicatization	Rocatec Soft	High-purity 30- μ m aluminum oxide, modified with silica (SiO ₂)	3M ESPE, Seefeld, Germany
Total-etch adhesive system for IDS	OptiBond FL	<i>Primer</i> : 2-hydroxyethyl methacrylate ethanol; 2-[2-(methacryloyloxy) ethoxycarbonyl] benzoic acid, glycerol phosphate dimethacrylate; <i>Adhesive</i> : 2-hydroxyethyl methacrylate, 3-trimethoxysilylpropyl methacrylate, 2-hydroxy-1,3-propanediyl bismethacrylate, alkali fluorosilicates (Na)	Kerr, Orange, USA
Silane/MDP for lithium disilicate	Monobond Plus	Alcohol solution of silane methacrylate, phosphoric acid methacrylate, and sulphide methacrylate	Ivoclar Vivadent, Schaan, Liechtenstein
Adhesive system for lithium disilicate	Adhese Universal	Phosphoric acid methacrylate, methacrylated carboxylic acid polymer, hydrophilic mono-functional methacrylate, hydrophilic/hydrophobic crosslinking dimethacrylate, hydrophobic crosslinking dimethacrylate	Ivoclar Vivadent, Schaan, Liechtenstein
Resin cement for lithium disilicate	Variolink Esthetic Dual Cure	<i>Monomer matrix</i> : urethane dimethacrylate, inorganic fillers (ytterbium trifluoride and spheroid mixed oxide), initiators, stabilizers, and pigments	Ivoclar Vivadent, Schaan, Liechtenstein
Etching for lithium disilicate	IPS Ceramic Etching Gel	5% hydrofluoric acid	Ivoclar Vivadent, Schaan, Liechtenstein
Lithium disilicate block for endocrown	IPS e.max CAD	SiO ₂ , Li ₂ O, K ₂ O, P ₂ O ₅ , ZrO ₂ , ZnO, Al ₂ O ₃ , MgO, coloring oxides	Ivoclar Vivadent, Schaan, Liechtenstein
Universal adhesive system for resin nanoceramic	Scotchbond Universal Adhesive	MDP phosphate monomer, dimethacrylate resins, HEMA, filler, ethanol, water, initiators, silane	3M ESPE, Seefeld, Germany
Resin cement for resin nanoceramics	RelyX Ultimate	Methacrylate monomers, radiopaque silanated fillers, initiators, stabilizers, and pigments	3M ESPE, Seefeld, Germany
Resin nanoceramic block for endocrown	Lava Ultimate	<i>Zirconia-silica nanocluster particles</i> : 20-nm diameter silica nanomers, 4 to 11 nm zirconia nanomers, silane coupling agent	3M ESPE, Seefeld, Germany

three fracture modes: 1) 'reparable' – cohesive or adhesive failure of restoration only (failure above CPL); 2) 'possibly reparable' – cohesive/adhesive failure with fragment and minor damage, chip or crack of underlying tooth structure (between acrylic resin base level and CPL); or 3) 'catastrophic' – root fracture that would require tooth extraction (fracture below acrylic resin base level) (Fig 5).

The fatigue resistance of the groups was compared using the Kaplan Meier survival analysis (for the number of cycles endured). The log rank post hoc test was used to analyze the influence of the endocrown material on the fracture resistance of the ETI at a significance level of 0.05.

The fracture load step at which the specimen failed was compared using Life Table analysis followed by the Wilcoxon test at a significance level of 0.05. At each time interval (defined by each load step), the number of specimens that started the interval intact and the number of specimens that fractured during the interval were counted, allowing the calculation of survival probability at each interval. For all statistical analyses, the level of significance was set at 95%. The data were analyzed with SPSS 23 statistical software.

Supplementary data from previous studies performed concomitantly by the same authors under strictly identical experimental conditions were combined with the present data for additional computation and comparison. The previous studies included CAD/CAM-fabricated lithium disilicate crowns bonded over: 1) FNp, a 2mm-ferrule ETI restored with a nanohybrid composite resin (Miris2; Coltene) core buildup without post ($n = 15$); 2) NfPf, a no-ferrule post-and-core buildup with fiber-reinforced post (ParaPost Fiber Lux; Coltene) and nanohybrid composite resin (Miris2) ($n = 15$); and 3) NfNpFR, a no-ferrule and no-post core buildup made of short-fiber-reinforced

composite resin (everX Posterior; GC) ($n = 15$). A schematic representation of the groups is shown in Figure 6. The detailed procedures are described elsewhere.^{14,17,21} The present study was a subset of a comprehensive experiment that shared the control groups.

Results

None of the 30 samples survived to the 140,000 cycles, thus the mean cycles to failure (Kaplan Meier analysis) and median load to failure (Life Table analysis) could be obtained. The endured cycles to failure of the lithium disilicate endocrowns ranged from 29,724 to 86,390 (Eld mean: $53,448 \pm 3,666$ SE cycles), and those of the resin nanoceramic endocrowns ranged from 32,487 to 82,985 (Erc mean: $52,397 \pm 4,396$ SE cycles). No statistical difference could be observed among the endocrown groups regarding the number of endured cycles at failure ($P = 0.844$). The applied load at failure is also an important factor to be evaluated. It ranged from 400 to 700 N for both endocrown groups, with mean values of 541 N and 512 N for Eld and Erc, respectively. No statistical difference could be observed among the endocrown groups regarding the load step at failure ($P = 0.652$).

The two endocrown groups (Eld and Erc) were also compared with additional data from previous studies using lithium disilicate crowns and various buildups: groups ($n = 15$) with ferrule and without post (FNp), without ferrule and with post (NfPf), and short-fiber-reinforced without ferrule and without post (NfNpFR) approaches. None of those additional 45 samples survived to all 140,000 cycles; the mean cycles to failure (Fig 7) and median load at failure (Fig 8) could be obtained for all 75 samples (5 groups; $n = 15$). The Kaplan Meier (cycles) and Life Table (load) survival curves are presented in Figures 9 and 10, respectively. The

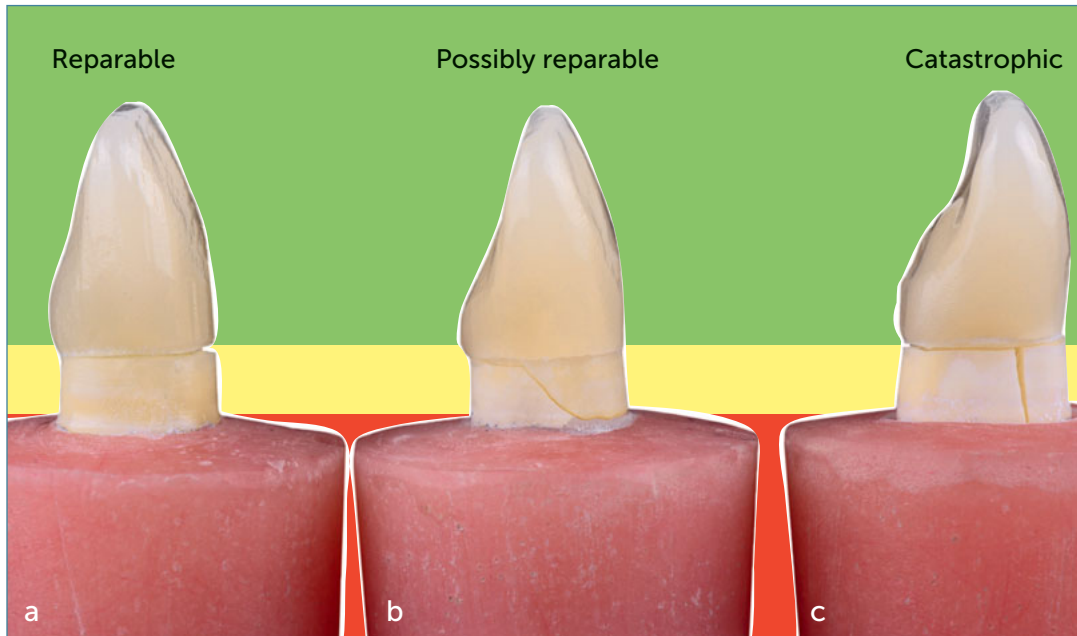


Fig 5 All specimens were analyzed and classified into one of three failure modes: 'reparable' (fracture occurred in the green area, above the cervical preparation limit (CPL) – cohesive or cohesive/adhesive fracture of restoration only; a); 'possibly reparable' (fracture occurred in the yellow area, between the resin acrylic base level and the CPL – cohesive/adhesive failure with fragment and minor damage, chip or crack of underlying tooth structure; b); 'catastrophic' (fracture occurred in the red area, below the acrylic resin base level – root fracture that would require tooth extraction; c).

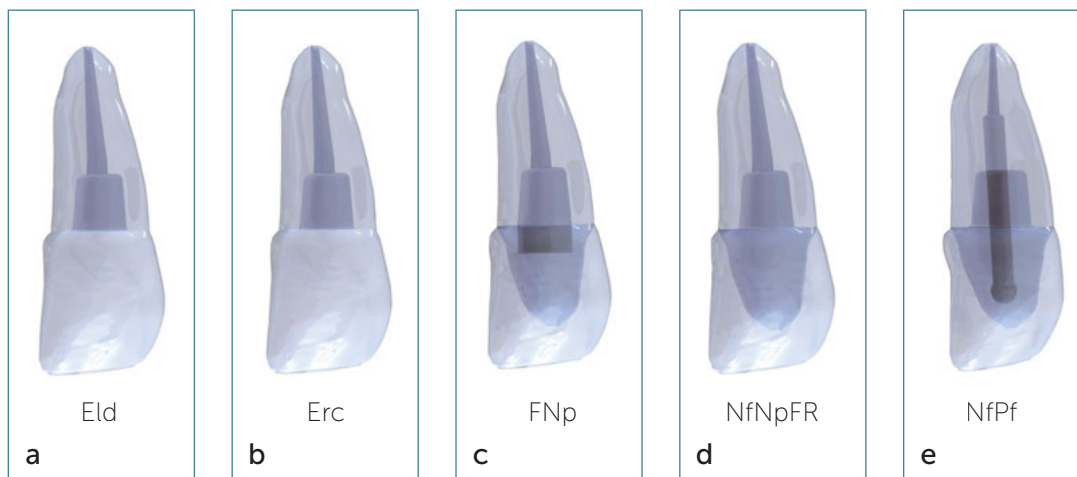


Fig 6 Schematic representation of the endocrown groups Eld and Erc (a and b), and supplementary groups from previous studies (c to e) FNp: with 2-mm ferrule and nano-hybrid composite resin core buildup without post; NfNpFR: a core buildup made of short-fiber-reinforced composite resin without ferrule and without post; NfPf: a post-and-core buildup with fiber-reinforced post and nano-hybrid composite resin without ferrule.

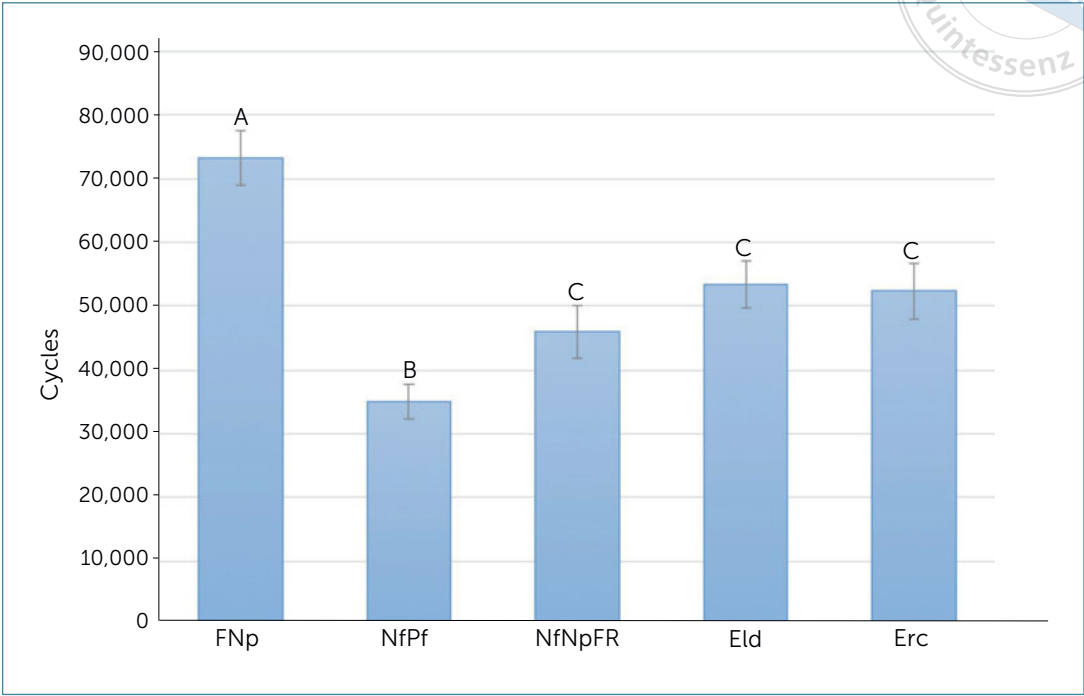


Fig 7 Mean survived cycles and standard errors: Kaplan Meier and log rank post hoc tests ($P < 0.05$) with different letters indicating significant differences. FNp: ferrule without post; NfPf: no ferrule with fiber post; NfNpFR: no ferrule, no post, and short-fiber-reinforced composite core buildup.

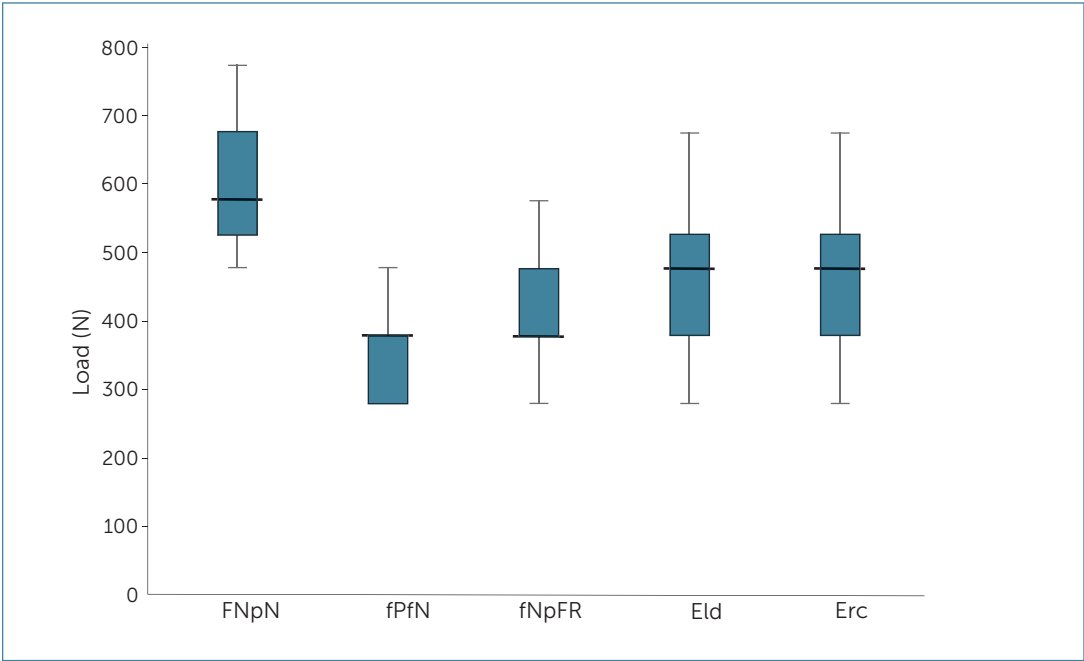


Fig 8 Box and whisker diagram of fracture loads presenting the median (bold black horizontal line), the minimum and maximum values (vertical 't' lines, or whiskers), the total number of samples ($N = 75$), and the interquartile range (blue box). FNp: ferrule without post; NfPf: no ferrule with fiber post; NfNpFR: no ferrule, no post, and short-fiber-reinforced composite core buildup.

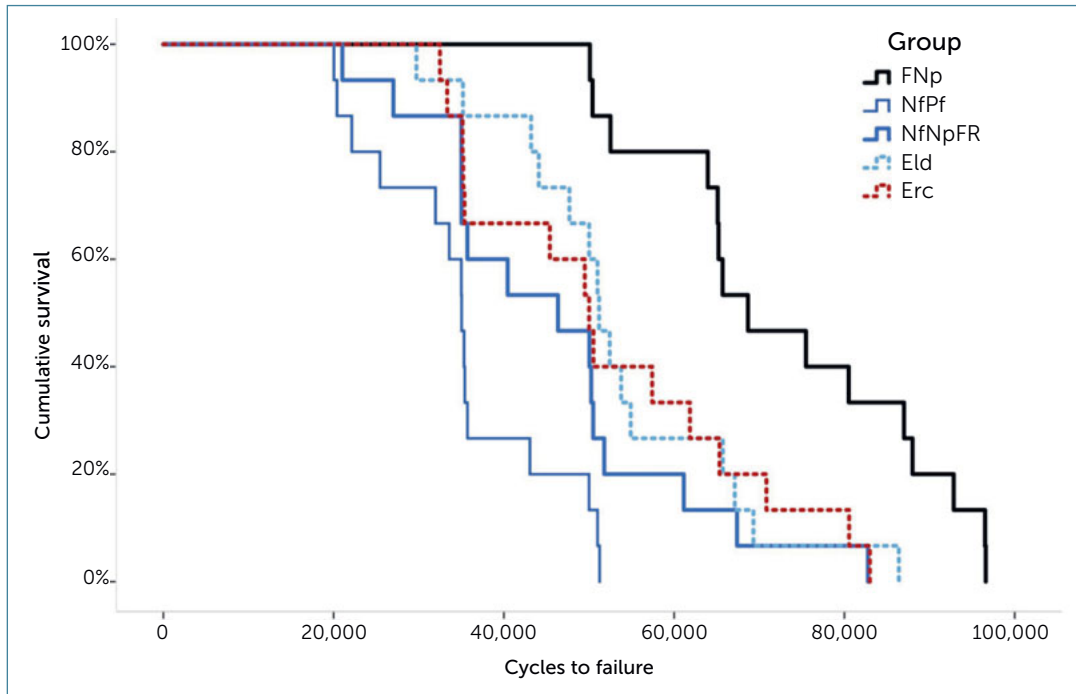


Fig 9 Kaplan Meier survival curves for all five groups (for better understanding of the effect of ferrule and the effect of post and overall comparison, FNp, NfPf, and NfNpFR groups from previous studies were included).

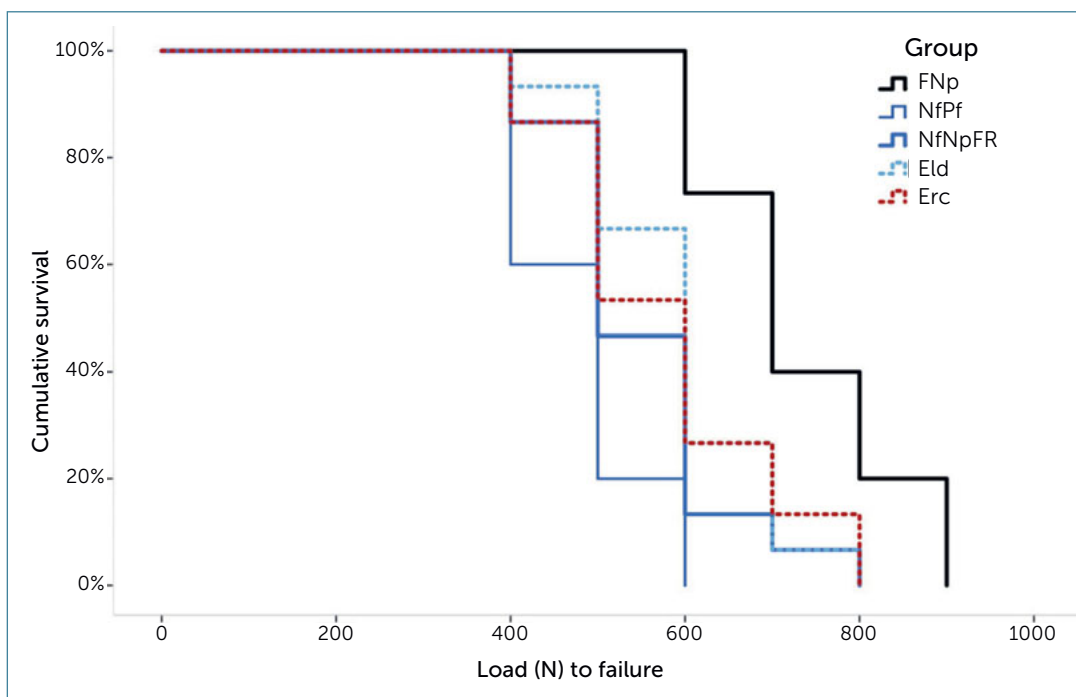


Fig 10 Life Table survival curves for all groups. At each time interval (defined by each load step), the number of specimens intact at the start of the time interval as well as the number of specimens that fractured during the interval were counted, allowing the calculation of survival probability at each interval.

mean cycles to failure ranged from the lowest value of $35,025 \pm 2687$ SE to the highest value of $73,244 \pm 4207$ SE for NfPf and FNp, respectively. The presence of ferrule significantly increased the performance of the ETIs tested in this study. Regarding cycles and load, the group with ferrule (FNp) outperformed the endocrown groups without ferrule (Eld and Erc). The endocrown groups outperformed the group with post (NfPf) for both criteria. The short-fiber-reinforced no-post core buildup group (NfNpFR) outperformed the group with a post (NfPf). There was no difference for either cycles or load between either endocrown groups and the NfNpFR group. The *P* values for cycles and loads for all group-by-group comparisons are presented in Table 3.

Considering the failure mode, the Erc group presented more favorable failures compared with the Eld group (80% and 73% non-catastrophic failures, respectively). The use of a post for retention generated 100% of catastrophic failures in the NfPf group, compared with 33% and 53% in the NfNpFR and FNp groups, respectively. The percentages of failure types for each group are presented in Figure 11.

Discussion

The present study evaluated the performance of lithium disilicate and resin nanoceramic endocrowns for the restoration of severely broken-down no-ferrule ETIs. The main null hypothesis was accepted, as no statistically significant differences could be found between the two endocrown materials. Since the results were compared with previously published data, two more hypotheses could be tested. The first additional hypothesis was rejected, since the presence of a ferrule improved the fatigue resistance compared with all other no-ferrule groups, regardless of material or technique. The second additional null hypothesis was

rejected too, since the use of a fiber post (including adhesive buildup and lithium disilicate crown) negatively affected the fatigue resistance and failure mode. Additionally, the use of a postless short-fiber-reinforced core buildup increased the fatigue resistance when compared with the classic approach with a fiber post.

The stepped-load protocol (accelerated fatigue test) using a closed-loop electromechanic system represents a balanced test between the conventional load-to-failure protocol and the time-consuming low-load high-cycle fatigue test, allowing a physiologic representation of mastication.^{46,47} This test strategy seems to provide a better simulation of the clinical conditions than static high-load tests. Therefore, the presented protocol appears to be the best compromise between available in vitro fatigue testing methods and clinical reality. To further challenge the restoration, the previously described load protocol with increasing loads from 100 to 1000 N and a frequency of 5 Hz was combined with an angle of force of 30 degrees concentrated at the incisal edge of the restorations to represent an extreme load configuration (worst-case scenario). No artificial periodontium was placed around the roots, as elastic films normally used for this purpose show degradation during fatigue testing.

One of the findings of previous studies was the occurrence of initial failure when restoring ETT with posts.^{14,17} This phenomenon is described as a wide gap opening at the margin between the crown and the root that propagates over time until complete catastrophic fracture. This indicates an adhesive failure at the crown-tooth lingual interface, possibly due to the bending forces during oblique loading in the test. Such initial failures did not occur when no-post approaches were tested. As described by Kishen,⁴⁸ the initial failure is considered

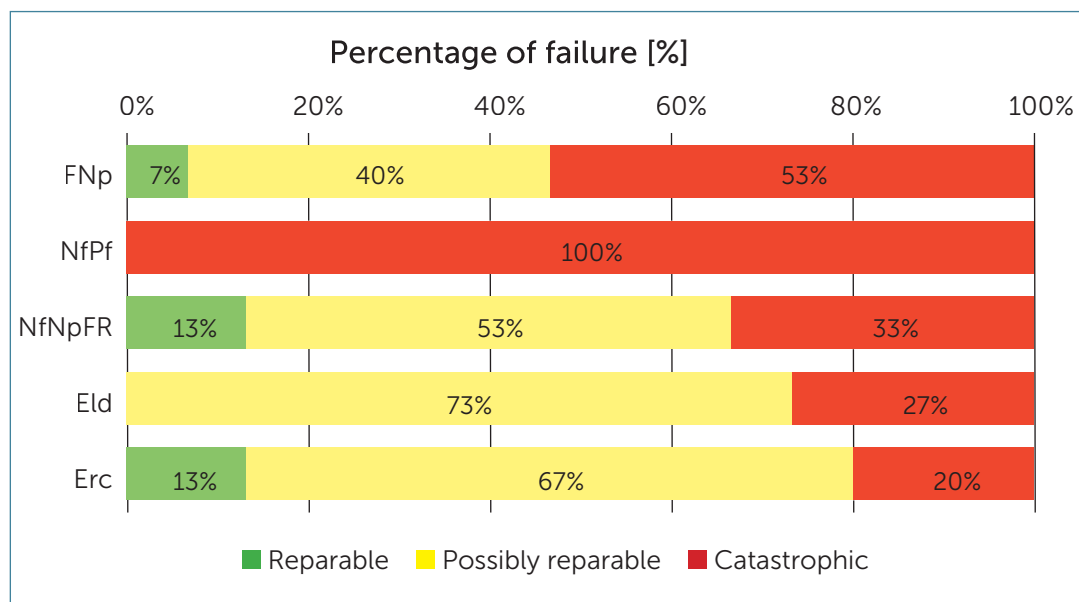
Table 3 *P* values for pairwise post hoc comparisons

	FNp	NfPf	NfNpFR	Eld	Erc
FNp	–	0.000*	0.000*	0.003*	0.003*
NfPf	0.000*	–	0.031*	0.000*	0.004*
NfNpFR	0.000*	0.049*	–	0.223	0.340
Eld	0.003*	0.004*	0.249	–	0.844
Erc	0.003*	0.023*	0.589	0.652	–

F: ferrule; Nf: no ferrule; Pf: fiber post; Np: no post; FR: short-fiber-reinforced; E: endocrown; Id: lithium disilicate; rc: resin nanoceramic

Dark shaded cells: *P* values for post hoc tests for cycles (Kaplan Meier followed by the log rank post hoc test). Light shaded cells: *P* values for post hoc tests for load (Life Table followed by Wilcoxon-Gehan test)

* Statistical difference between groups (*P* < 0.05)

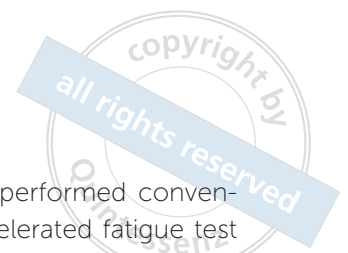
**Fig 11** Percentage of samples per group for each type of failure mode.

an important factor that has several mechanical and microbiologic implications. Thus, for NfPf, the initial failure was used for comparison.

The instant complete failure of no-post restorations is a preferable scenario because the patient is more likely to consult immediately for repair. On the other hand, the slow-propagating crack inherent to the

initial failure phenomenon (associated with post-and-core buildups) is often undiagnosed and ends up with catastrophic consequences (infiltration, caries, root fracture, bone loss etc.).

The results of the present study demonstrated that using CAD/CAM composite resin blocks instead of lithium disilicate ceramic was not detrimental to



fatigue resistance, even though the flexural strength of resin nanoceramics are substantially inferior to those of lithium disilicate (see Table 1). Composite resin CAD/CAM restorations have been associated with acceptable and reliable performance when compared with ceramics.⁴⁹⁻⁵¹ Despite the relatively recent popularity of composite resin CAD/CAM blocks and endocrowns themselves, few studies have combined the two. Gresnigt et al³⁴ evaluated IPS e.max CAD and Lava Ultimate materials for the endocrown restoration of endodontically treated molars and reported no statistically significant differences in axial static loading fracture resistance compared with conventional crown and core buildup approaches. Different results were found in the study by El Ghoul et al,⁸ wherein lithium disilicate had better fracture resistance than resin nanoceramics for static loading of molar endocrowns, and endocrowns presented higher fracture strength than conventional crowns. A study by Hassouneh et al⁹ comparing the fracture resistance of no-ferrule premolar endocrowns made from different CAD/CAM materials showed a better mechanical performance of composite over lithium disilicate endocrowns. Differently from the present study, the group of zirconia crowns luted over a post and buildup had better fracture resistance than endocrowns, but 90% of the failures were catastrophic compared with 60% for endocrowns. Considering the anterior dentition, a study by Silva-Sousa et al¹⁰ evaluated the effect of ferrule and restoration design (lithium disilicate endocrown versus conventional crown) on the fracture resistance of human canines. In contrast to the findings of the present study, the presence of ferrule did not influence the resistance when using a fiber post and regular crown, although it did positively influence it when using an endocrown. In that study, conventional crown groups outperformed endocrown groups, whereas in the present

study, endocrowns outperformed conventional crowns. The accelerated fatigue test performed under oblique loading in the present study challenged the weakened anterior root cyclically, differently to axial static loading that usually provides a greater range of fracture resistance values and therefore greater standard deviations and *P* values. Also, the IDS for adhesion optimization for the indirect restorations used in the present study might have played an important role in the better micromechanical retention of the endocrowns. The adhesion enhancement of IDS has already been proven in other in vitro and clinical studies.^{29,43-45}

The lower percentage of catastrophic failures found in composite resin endocrowns may be due to better stress distribution, as its lower elastic modulus may concentrate less stress on the root than the ceramic endocrown.^{37,52} The more biomimetic behavior of composite resin includes its capability of causing less opposing enamel wear than glass-ceramics.⁵³ Some concerns arise about the esthetics of the composite resin material used for endocrown fabrication because blocks are monochromatic and an esthetic modification of the raw workpiece after milling may be necessary, depending on the esthetic needs of the patient.⁵² Thus, future research should focus on novel clinical approaches to use CAD/CAM materials as a core buildup for veneers (veneered endocrowns) or other esthetic enhancements.⁵⁴

In the present study, endocrown restorations performed well, even presenting better failure modes and higher values in both endured cycles and load than conventional crowns bonded to adhesive post-and-core buildups. When comparing the endocrowns with the additional data from the no-ferrule and no-post approach (NfNpFR), no statistically significant differences were found regarding the fatigue resistance. The similar results between



core buildup and endocrowns could be due to the enhanced mechanical behavior of short-fiber-reinforced composite resin core buildup compared with regular composite resin. Mechanical enhancement of fiber-reinforced composite has already been shown by other studies.⁵⁵⁻⁵⁸ Garoushi et al⁵⁹ compared incisors without ferrule restored with full direct crowns made of regular particulate filler composite resin, with and without fiber posts, and short-fiber-reinforced composite resin. The fiber-reinforced composite resin outperformed all the other groups in static load. Moreover, the endocrowns presented the advantage of reducing the number of interfaces of restorative materials. They also prevented polymerization shrinkage. The volumetric shrinkage on the indirect restoration was limited to the cementation gap instead of the entire buildup. Even though it has been claimed that bulk-fill approaches can be used to limit polymerization shrinkage stress, recent studies demonstrate that bulk-fill shrinkage could still interfere with the integrity of the adhesive interface.⁶⁰

Despite the different attempts to restore ETIs, vertical root fractures are still encountered in daily clinical practice.¹⁹ There was a significant difference when comparing the endocrown failure modes with those of the post-and-core group (NfPf). Among the endocrowns, at least 73% of the failures were non-catastrophic, whereas 100% unreparable root fractures were found in NfPf. Similar findings exist in other studies on the posterior dentition.⁶¹

It has already been proven that, in the presence of ferrule, fatigue resistance is not influenced by the presence of a post in ETIs.¹⁷ In fact, the use of a post was detrimental to the failure mode. For that reason, a no-post approach with ferrule (FNp) was selected for comparison with the results of the present study. Thus, even

though the endocrowns outperformed the post-and-core buildup group in a no-ferrule condition, the ferrule effect significantly increased the fatigue resistance of the ETIs, as has been confirmed by other studies.^{62,63} The 4-mm-deep internal ferrule proposed in the present study did not fully compensate the absence of ferrule, although the failure modes among endocrowns were more favorable compared with the ferrule group. The large internal ferrule preparation was performed to simulate a worst-case scenario, with reduced dentinal wall thickness, as well to provide enough material volume to withstand the loading condition and more area for the adhesive luting of endocrowns or bonding of core buildups.

The limitations of this *in vitro* study include the lack of correlation between the *in vitro* simulation and the *in vivo* aging as well as the lack of additional challenges of thermocycling and bacterial activity, beyond the mechanical challenge of mastication. Thus, randomized clinical trials with no-post approaches should be carried out so as to better understand the real clinical potential of the techniques and materials that were observed in the present study. Different preparation designs and dimensions of endocrowns should also be studied to cover the multiple clinical aspects of severely broken-down ETIs.

Conclusion

Within the limitations of the present study, it is possible to conclude that, when restoring a broken-down ETI:

1. Endocrowns, while not fully compensating for the absence of ferrule (as the ferrule effect outperformed all no-ferrule approaches), provided a superior performance compared with the use of a fiber post with composite resin buildup.

2. The post-and-core approach not only failed to increase the fatigue resistance, but also always resulted in catastrophic root fractures preceded by a clinically undiagnosable initial failure phenomenon.
3. Indirect CAD/CAM endocrowns made from resin nanoceramics may enhance the failure mode without jeopardizing the fatigue resistance compared with lithium disilicate endocrowns.

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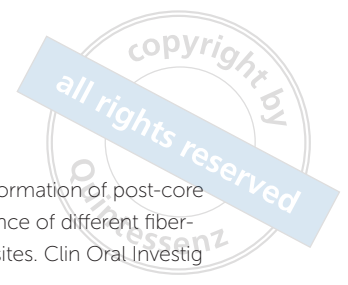
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