The effect of post, core, crown type, and ferrule presence on the biomechanical behavior of endodontically treated bovine anterior teeth

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Statement of problem. Unresolved controversy exists concerning the remaining coronal tooth structure of anterior endodontically treated teeth and the best treatment option for restoring them.

Purpose. The purpose of this study was to evaluate the effect of post, core, crown type, and ferrule presence on the deformation, fracture resistance, and fracture mode of endodontically treated bovine incisors.

Material and methods. One hundred and eighty bovine incisors were selected and divided into 12 treatment groups (n=15). The treatment variations were: with or without ferrule, restored with cast post and core, glass fiber post with composite resin core, or glass fiber post with fiber-reinforced core, and metal- or alumina-reinforced ceramic crown (n=15). The restored incisors were loaded at a 135-degree angle, and the deformation was measured using strain gauges placed on the buccal and proximal root surfaces. Specimens were subsequently loaded to the point of fracture. Strain and fracture resistance results were analyzed by 3-way ANOVA and Tukey HSD tests (α=.05).

Results. Ferrule presence did not significantly influence the buccal strain and fracture resistance for the ceramic crown groups, irrespective of core and crown type. Ferrule presence resulted in lower strains and higher fracture resistance in the metal crown groups, irrespective of core. The cast post and core showed lower strain values than groups with glass fiber posts when restored with metal crowns.

Conclusions. Core type did not affect the deformation and fracture resistance of endodontically treated incisors restored with alumina-reinforced ceramic crowns. The presence of a ferrule improved the mechanical behavior of teeth restored with metal crowns, irrespective of core type. (J Prosthet Dent 2010;104:306-317)

Clinical Implications

Conservation of tooth structure and proper selection of restorative materials are crucial for a favorable prognosis of endodontically treated teeth. Alumina-reinforced ceramic crowns with glass fiber posts seem to be the best choice of the systems tested to restore an endodontically treated incisor. When using metal crowns for teeth without remaining coronal tooth structure, the use of a cast post and core seems to be the best option.

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It has been reported that endodontically treated teeth undergo changes in mechanical properties,[1,2] most significantly, a reduction in fracture strength.[3,4] In some studies, however, changes in properties such as modulus of elasticity and proportional limit,[5] compressive strength,[6] or brittleness have not been observed for these teeth.[7] Reduction in the strength of endodontically treated teeth is therefore most likely caused by the degradation in structural integrity following the substantial loss of tooth structure, which occurs during endodontic therapy and cavity preparation.[8] The longevity of a restored tooth thus depends on the amount of remaining tooth structure and on the efficiency of the restorative procedure used to replace lost structural integrity.[9,10]

The amount of internal dentin structure has been directly correlated with the fracture resistance of endodontically treated teeth.[9,11,12] It has been reported that the presence of a 2.0-mm crown ferrule surrounding remaining tooth structure enhanced fracture resistance of anterior teeth which were restored with a cast post and core and metal ceramic crowns.[1,13] Studies have shown that increasing the height of the ferrule increases the resistance form of the tooth.[14,15] Most studies have evaluated the effect of ferrules in combination with metal crowns.[1,14,16-18] More recently, ceramic crowns have become popular due to improvements in their mechanical properties, in combination with enhanced esthetics.[19,20] However, the mechanical performance of ceramic crowns bonded to the dental structure remains questionable when compared with metal ceramic crowns.[21]

In clinical practice, teeth with minimal coronal structure are seen with high frequency. When the remaining tooth structure is not sufficient to retain a crown, a post is indicated to provide retention and to improve the distribution of functional loads to the root.[11,22] Among the most common options are cast post and cores and prefabricated metal or fiber posts.[16] In vitro studies that compared cast post and cores and prefabricated posts have yielded conflicting results.[17] Generally, a tooth restored with a stiff cast-and-post system was observed to withstand a higher load before fracturing, but the fracture was more often catastrophic and resulted in tooth extraction.[23] Prefabricated post systems demonstrated less strength, but generally resulted in repairable fracture modes.[24] These differences in the mechanical behavior of teeth restored with different post systems have been attributed to the differences in stiffness that affect the distribution of stress in the tooth.[25-28]

Fracture resistance of restored teeth and the mode of failure are thus the result of the interaction between multiple mechanical properties.[29] These can be investigated with both destructive testing and also nondestructively by measuring deformation.[24,30,31] For example, deformation of tooth structure has been measured using strain gauges in studies that analyzed the influence of restorative materials,[30] endodontic therapy,[32] or post insertion.[24,33]

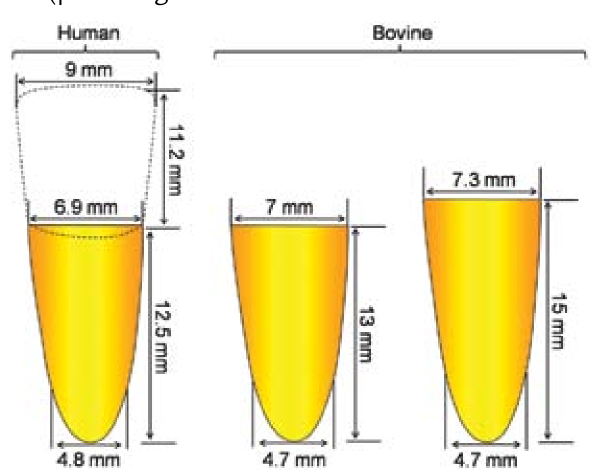
The purpose of this in vitro study was to investigate the effectiveness of different procedures for restoring the function of severely compromised endodontically treated incisors. The null hypothesis was that the mechanical behavior (expressed as deformation and fracture) would not be affected by the amount of remaining tooth structure (providing a ferrule or not), nor by the types of post, core, and crown.

MATERIAL AND METHODS

Specimen preparation

One hundred and eighty bovine incisors were selected for this study. The selected incisors had similar dimensions (coronal volume within 10% of the average), roots without curvature, were free of cracks or defects, and had been stored for no longer than 3 months.[34-36] All external debris was removed with a hand scaler, and the teeth were stored in 0.2% thymol solution (Isofar, Duque de Caxias, Brazil). The anatomic crowns of all teeth were sectioned perpendicular to the long axis, using a water-cooled diamond disk (no. 7020; KG Sorensen, Barueri, Brazil), up to 15.0 mm from the apical limit in the specimens with ferrule (n=90; F groups), and up to 13.0 mm from the apical limit in the specimens without ferrule (n=90; Nf groups). The mean dimensions of human maxillary central incisors[37] and bovine mandibular incisors are shown in Figure 1.

Root canals were instrumented to the full extension using no. 2 and 3 Gates-Glidden drills (Dentsply Maillefer, Ballaigues, Switzerland). Next, a no. 4 Gates-Glidden drill (Dentsply Malleifer) was used in the cervical and middle thirds of the root canal. Canals were rinsed with 1.0%



1 Mean dimensions of human maxillary central incisor and of bovine roots used.

sodium hypochlorite (Miyako do Brasil, Guarulhos, Brazil) and physiological saline (Avante Pharma, Belo Horizonte, Brazil), dried with paper points, and obturated with gutta-percha (Dentsply, Petrópolis, Brazil) and calcium hydroxide-based cement (Sealer 26; Dentsply).[2] The specimens with ferrules were prepared with a cylindrical diamond rotary cutting instrument (no. 3215; KG Sorensen) mounted in a high-speed handpiece (EXTRAtorque 605 C; KaVo do Brasil, Joinville, Brazil), creating a 2.0-mm-high circular ferrule in the coronal region. Post space was obtained initially with a heated instrument (M-Series Pluggers; Dentsply Maillefer), and the residual gutta-percha was then removed with Gates-Glidden drills, standardizing the post space at 8.0 mm for the groups without ferrule and 10.0 mm for the groups with ferrule, preserving 5.0 mm of gutta-percha at the apex. Next, root canals were enlarged with a 1.0- to 1.6-mm-diameter conical drill (Exacto drill no. 3; Angelus Science and Technology, Londrina, Brazil) to 8.0 mm for the groups with no ferrule and 10.0 mm for the groups with ferrule, developing standardized diameters for the cast post and cores, as was done for the glass fiber prefabricated system.

The roots were embedded in polystyrene resin (AM 190 resin; AeroJet, Santo Amaro, Brazil) below the cervical limit, which, in this situation, was where the crown had been separated from the root. Roots with no ferrule were embedded 2.0 mm below this limit, and roots with ferrule, 4.0 mm below. The periodontal ligament was simulated using polyether impression material (Impregum Soft; 3M ESPE, St. Paul, Minn).[38,39] To accomplish this, root surfaces were dipped into molten wax up to 2.0 mm apically from the cervical limit for groups without a ferrule and 4.0 mm for groups with a ferrule. The resulting wax layer was 0.2 to 0.3 mm thick. A radiographic film with a centralized circular opening (IBF, Rio de Janeiro, Brazil) was used to stabilize the teeth for the embedding procedure. The teeth were placed with the crown facing down into the opening in a wooden board, leaving the root in a vertical position perpendicular to the supporting radiographic film. Then, a plastic cylinder 25.0 mm in diameter (no. 10.12.178.7 PVC; Tigre, Joinville, Brazil) was placed around the root and fixed in position with cyanoacrylate resin adhesive (Super Bonder; Loctite, Itapeví, Brazil) and wax. The autopolymerizing polystyrene resin (AM 190 resin; AeroJet) was manipulated according to manufacturer's instructions and inserted into the cylinder. After polystyrene resin polymerization, the teeth were removed from the cylinder, and the wax was removed from both the root surface and cylinder. Impression material (Impregum Soft; 3M ESPE) was placed into the resin cylinders, the teeth were reinserted, and the excess polyether material was removed with a scalpel blade.[38,39]

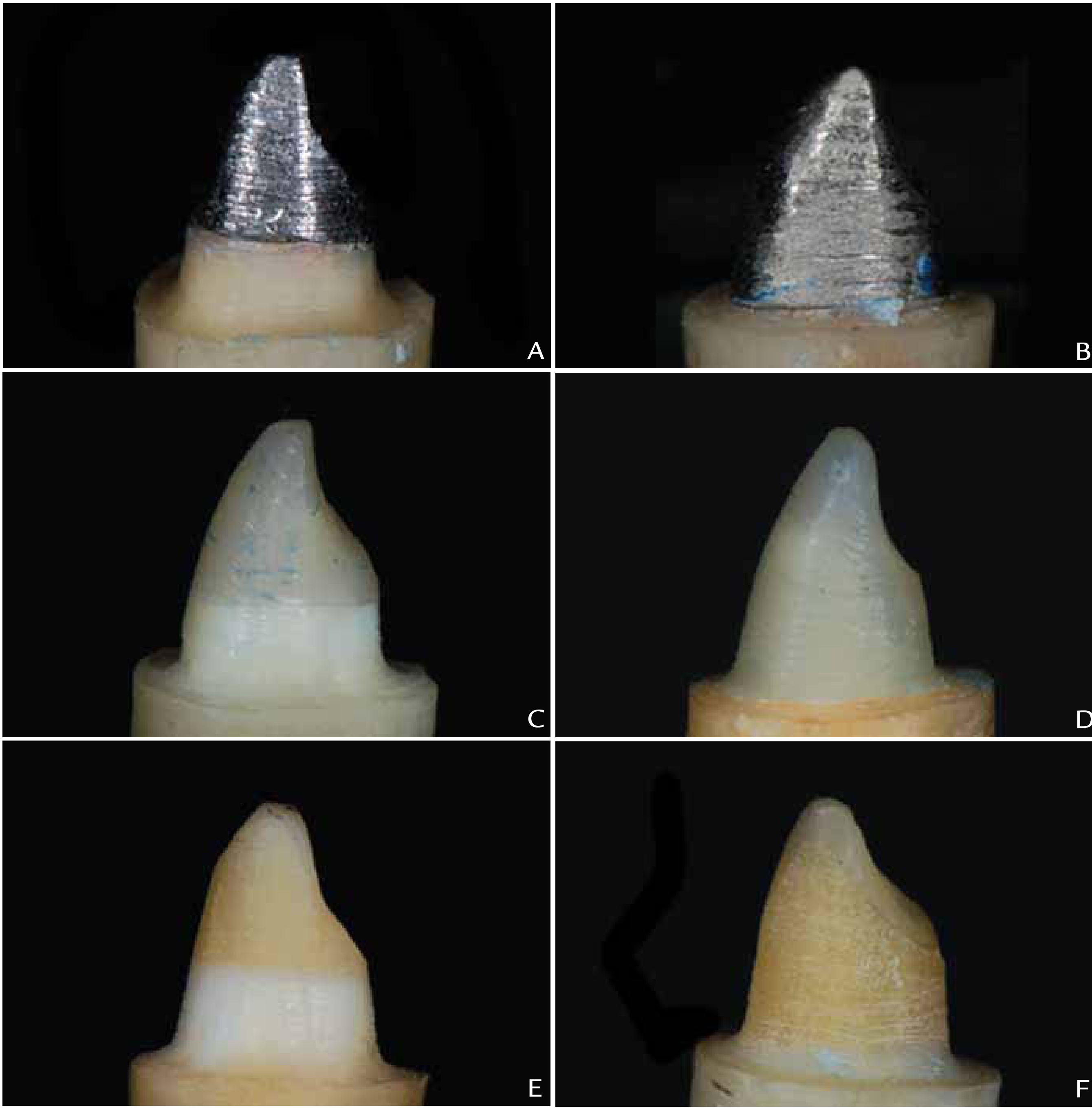
Restoration fabrication

The F and Nf groups were both divided into 3 subgroups (n=30): cast post and core (Cpc); glass fiber post with composite resin core (Gfr); and glass fiber post with fiber-reinforced core (Gfc). Finally, each subgroup was divided into 2 other subgroups (n=15), with the definitive restorations being metal crowns (Mc) and alumina-reinforced ceramic crowns (Cc) (Fig. 2).

Groups were then classified as follows: (1) FCpcMc, root with ferrule, restored with cast post and core and metal crown; (2) NfCpcMc, root without ferrule, restored with cast post and core and metal crown; (3) FCpcCc, root with ferrule, restored with cast post and core and ceramic crown; (4) NfCpcCc, root without ferrule, restored with cast post and core and ceramic crown; (5) FGfrMc, root with ferrule, restored with glass fiber post, composite resin core, and metal crown; (6) NfGfrMc, root without ferrule, restored with glass fiber post, composite resin core, and metal crown; (7) FGfrCc, root with ferrule, restored with glass fiber post, composite resin core, and ceramic crown; (8) NfGfrCc, root without ferrule, restored with glass fiber post, composite resin core, and ceramic crown; (9) FGfcMc, root with ferrule, restored with glass fiber post, fiber-reinforced core, and metal crown; (10) NfGfcMc, root without ferrule, restored with glass fiber post, fiber-reinforced core, and metal crown; (11) FGfcCc, root with ferrule, restored with glass fiber post, fiber-reinforced core, and ceramic crown; (12) NfGfcCc, root without ferrule, restored with glass fiber post, fiber-reinforced core, and ceramic crown.

For the cast post-and-core fabrication, prefabricated polycarbonate patterns (Nucleojet; Angelus Science and Technology) were used. The patterns were aligned using autopolymerizing acrylic resin (Duralay; Reliance Dental Mfg Co, Worth, Ill) in the post space until passive retention was obtained. As root canals had been previously enlarged with a conical bur (1.0- to 1.6-mm diameter; Angelus Science and Technology), the plastic patterns were standardized with a mean diameter of 1.4 mm and 0.9 mm in the coronal and apical portions, respectively. Subsequently, the individual patterns were adjusted on each respective specimen, standardizing the core height at 6.0 mm for the Nf group and 4.0 mm for the F groups. The patterns were invested, cast in nickel-chromium alloy (NiCr; Talladium do Brasil, Curitiba, Brazil) and airborne-particle abraded with 50-µm aluminum oxide particles (Aluminum Oxide; Pasom, São Paulo, Brazil) under 2 bars of pressure for 10 seconds.

Prefabricated glass fiber posts (Exacto no. 3; Angelus Science and Technology) with 1.4-mm and 0.9-mm diameters in the coronal and apical portions, respectively, were cleaned with a 70% alcohol solution (Miyako do Brasil) and treated with a 1-bottle silane coupling agent (Silano; Angelus Science and Technolo-



2 Representative specimens: A, With ferrule, restored with cast post and core (FCpc). B, Without ferrule, restored with cast post and core (NfCpc). C, With ferrule, restored with glass fiber post and composite resin core (FGfr). D, Without ferrule, restored with glass fiber post and composite resin core (NfGfr). E, With ferrule, restored with glass fiber post and fiber-reinforced core (FGfc); F, Without ferrule, restored with glass fiber post and fiber-reinforced core (NfGfc).

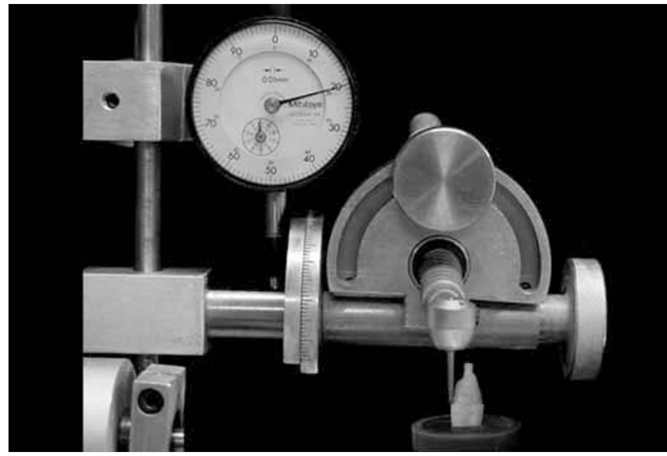
gy) for 1 minute. The fiber-reinforced cores (Reforcore; Angelus Science and Technology) were treated using the same protocol, following the manufacturer's recommendations.

For post cementation, post spaces were cleaned with 1.0% sodium hypochlorite solution (Miyako do Brasil), rinsed with water, and dried with paper points (Denstply). The self-adhesive resin cement (RelyX Unicem; 3M ESPE) was manipulated according to manufacturer instructions and used for luting all posts. The cementation process was standardized with a 500-g load applied to the specimens for 5 minutes and at every luting step.[24] The fiber-reinforced cores were also luted with the self-adhesive resin cement over the glass fiber posts. Each surface of the specimens was light polymerized for 40 seconds with a halogen unit (XL3000; 3M ESPE) at 800 mW/cm^2.

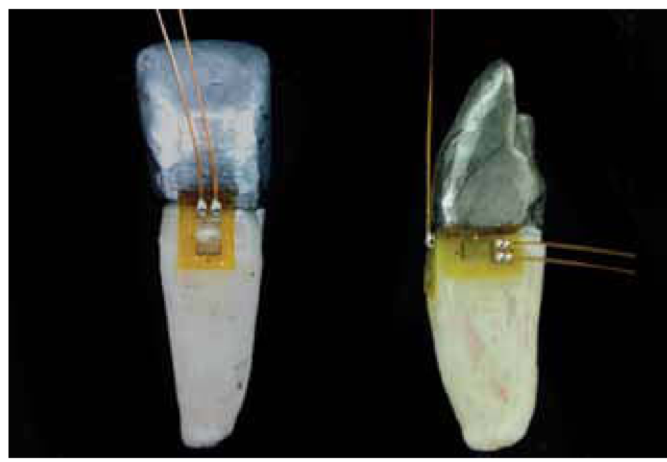
The composite resin cores (Filtek Z250; 3M ESPE) were standardized with a 0.25-mm-thick acetate matrix (Bio-art, São Carlos, Brazil) molded over the Cpc specimens in a vacuum-forming machine (Plastivac P7;

Bio-art).[24] The composite resin was added into the acetate matrix in 2.0-mm increments. Each increment was light polymerized for 40 seconds with a halogen unit (XL3000; 3M ESPE) at 800 mW/cm^2.

Complete crown coverage preparations featuring 1.5 mm of axial reduction and 6 degrees of axial convergence of the walls were accomplished with a tapered rounded-end diamond rotary cutting instrument (no. 4138; KG Sorensen) mounted in a cavity preparation machine.[40] This machine consisted of a high-speed handpiece (EXTRAtorque 605 C; KaVo do Brasil) coupled to a mobile base. The mobile base moves vertically and horizontally with 3 precision micrometric heads (152-389; Mitutoyo Sul Americana Ltda, Suzano, Brazil), attaining a 0.002-mm level of accuracy (Fig. 3). After the preparations were completed, specimens were manually finished with an extra-fine-grit diamond rotary cutting instrument (no. 3145FF; KG Sorensen). The cervicoincisal height remained at 6.0 mm. Impressions of the coronal portion of the specimens were made with a 2-step technique, using a polyether impression material (Impregum Soft; 3M ESPE). After 1 hour, the impressions were poured in type IV stone (Durone IV; Dentsply).



3 Specimen during preparation positioned in preparation machine.

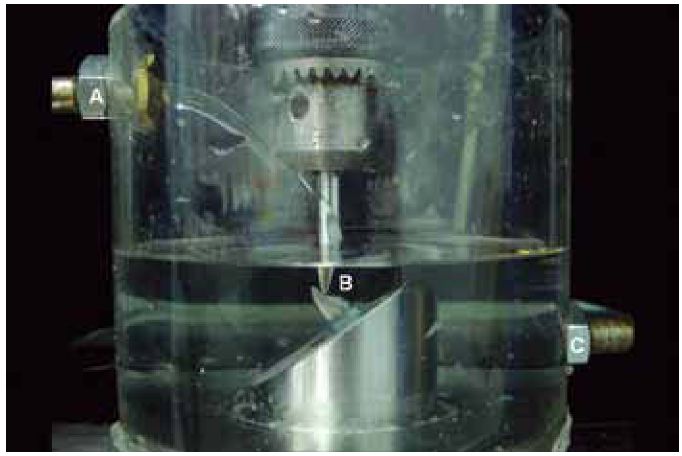


4 Strain gauges attached at coronal cervical limit on buccal and proximal surfaces.

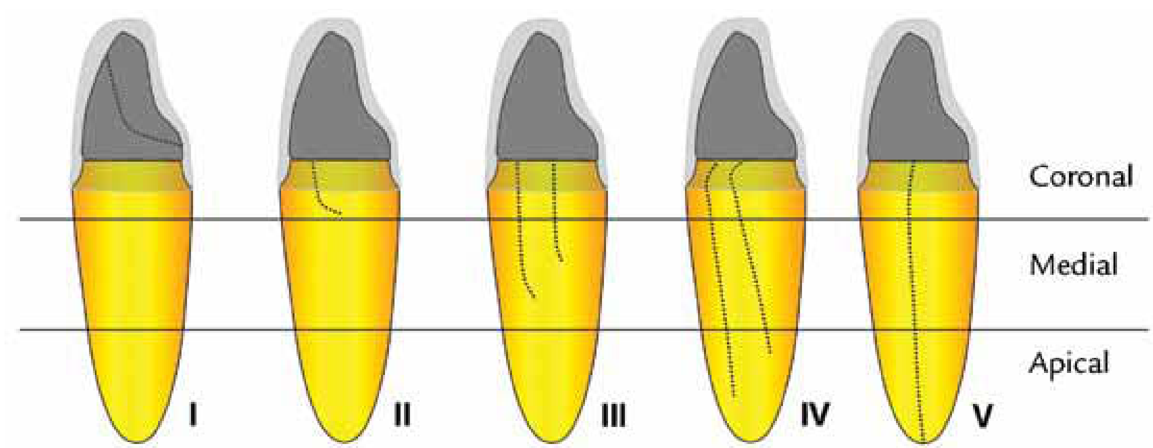
Half of the specimens of each subgroup were restored with metal crowns (Mc), and the other half with alumina-reinforced ceramic crowns (Cc). A standard crown with a lingual elevation of 1.0 mm for load application was fabricated in composite resin (Filtek Z250; 3M ESPE), from which a silicone matrix was made (IQ 428 Rubber; AeroJet). Heated liquid wax (PK green wax opaque; Kota Imports, São Paulo, Brazil) was inserted in this matrix, followed by one of the gypsum dies, resulting in the formation of a crown wax pattern. The patterns were invested and cast in nickel-chromium alloy (NiCr; Talladium do Brasil). The ceramic crown copings were made with a glass-infiltrated alumina system (Vitro-Ceram/Alumina; Angelus Science and Technology) and sequentially veneered with a conventional feldspathic ceramic system (AllCeram; Dentsply Ceramco, Burlington, NJ). Only the metal crowns were airborne-particle abraded, with 50-μm aluminum oxide (Aluminum Oxide; Pasom) under 2 bars of pressure for 10 seconds. Subsequently, both metal and ceramic crowns were cemented with a self-adhesive resin cement (RelyX Unicem; 3M ESPE), manipulated and activated according to manufacturer instructions.

Strain measurement tests

To measure the tooth deformation, 2 strain gauges (PA-06-060OBG-350LEN; Excel Sensores, São Paulo, Brazil) were attached to 5 specimens of each group 24 hours after tooth preparation. One gauge was placed on the buccal surface, parallel to the long axis, and the other on the proximal surface in a transverse direction; both were 1.0 mm below the cervical limit of the root (Fig. 4).[24] According to manufacturer information, the base material of these gauges consists of a polyimide and metal constantan film, with temperature self-compensation for steel. The strain gauge grid had an area of 4.1 mm^2 and an electrical resistance of 350 Ω. Strain gauges used for this study had a gauge factor of 2.12.[24,30] The gauge factor is a constant describing the proportional relationship between electrical resistance variation and strain. The electrical resistance of each strain gauge was periodically verified with a digital multimeter (Mesco DM-1000; Meastak Technology and Trade Ltd,



5 Fracture resistance test performed in water circulation device. A, Water input. B, Wedge-shaped tip. C, Water output.



6 Fracture mode classification: (I) post or core fracture; (II) root fracture in cervical third; (III) root fracture in middle third; (IV) root fracture in apical third; (V) vertical root fracture.

São Paulo, Brazil). For the strain gauge attachment, the root surface was etched with 37% phosphoric acid for 15 seconds (Condac 37; FGM, Joinville, Brazil), rinsed with water, and air dried. The strain gauges were bonded with a cyanoacrylate resin adhesive (Super Bonder; Loctite) and connected to a data acquisition device (ADS0500IP; Lynx, São Paulo, Brazil). In addition, a control specimen, with 2 strain gauges attached but not subjected to loading, was mounted adjacent to the tested tooth to compensate for temperature fluctuations due to gauge electrical resistance or local environment.[30]

The specimens with strain gauges were subjected to a nondestructive ramp-load from 0 to 100 N using a mechanical testing machine (EMIC DL2000; EMIC, São José dos Pinhais, Brazil).[24] The load was applied on the lingual surface, at a 135-degree angle to the long axis of the tooth, using a wedge-shaped tip. The crosshead speed was 0.5 mm/min. The data were recorded on a computer that performed the signal transformation and data analysis (AqDados 7.02 and AqAnalysis; Lynx). Data from all strain gauges were acquired at 3 Hz. Data for each region showed normal and homogeneous distribution and were statistically analyzed by 3-way analysis of variance (ANOVA) followed by Tukey Honestly Significant Difference (HSD) test (α=.05).

Fracture tests

Subsequently, all specimens were loaded to fracture using the same compressive loading design as used during the strain gauge tests. To standardize the temperature (37°C) and moisture (100%) during the fracture resistance test, a water circulation device (Federal University of Uberlândia, Uberlândia, Brazil) was used (Fig. 5).[24] This device consists of an acrylic resin cylinder, 150.0 mm in diameter and 200.0 mm in height, fixed on a steel base with 2 water circulators, and linked to a water receptacle with a continuous water spraying system and digital heater (Q215M2; Quimis, Diadema, Brazil). The applied force at fracture was recorded by the testing machine's software (TESC; EMIC), which detected any sudden load drop in its load-cell during the compression tests.

Fracture resistance data were analyzed with 3-way ANOVA followed by Tukey's HSD test (α=.05). Fractured specimens were visually evaluated to determine the fracture modes using a classification system modified from Zhi-Yue and Yu-Xing[1]: (I) post or core fracture; (II) root fracture in the cervical third; (III) root fracture in the middle third; (IV) root fracture in the apical third; (V) vertical root fracture (Fig. 6).

RESULTS

Buccal strains

The mean and standard deviation values for the strains (μS) at the buccal root surface are shown in Table I. The factors ferrule (P<.001), crown (P<.001), and the interactions between 2 factors, ferrule and core (P=.105) and ferrule and crown (P=.004), were significant for the buccal strain values, as shown by the 3-way ANOVA (Table II). The factors core (P=.130), the interaction between 2 factors, ferrule and core (P=.105), and the interaction between 3 factors (P=.289) were not significant.

No significant difference was found between the buccal strain values within the ferrule groups (F). There was also no significant difference between the buccal strain values within the groups with alumina-reinforced ceramic crowns (Cc). Within the group without ferrule (Nf), buccal strain values were significantly higher (P<.001) when a metal crown was combined with glass fiber posts (NfGfrMc and NfGfcMc).

Proximal strains

The mean and standard deviation values for the strains (μS) at the proximal root surfaces are shown in Table III. The factors ferrule (P=.017) and crown (P=.005) were significant for the proximal strain values, as shown by the 3-way ANOVA (Table IV). The factors core (P=.700), the interaction between 2 factors, ferrule and core (P=.683), ferrule and crown (P=.556), and core and crown (P=.662), and the interaction between 3 factors, ferrule, core, and crown (P=.535) were not significant.

The proximal strain values for groups with metal crowns (Mc) were significantly higher (P=.005) than for groups with alumina-reinforced ceramic crowns (Cc), irrespective of core or ferrule presence. The groups without ferrule (Nf) showed significantly higher (P=.017) proximal strains than the groups with ferrule (F), irrespective of core or post type. Glass fiber posts produced significantly higher (P=.023) proximal strains than the cast post and core in the groups with a metal crown but no ferrule.

Fracture resistance and mode

The mean fracture resistance (N) and standard deviation values are shown in Table V. The factors ferrule presence (P<.01), crown type (P=.004), and the interaction between these factors (P=.016) were significant for the fracture resistance, as shown by the 3-way ANOVA (Table VI). The factor core type (P=.629), the interaction between 2 factors, core and ferrule (P=.364) and core and crown (P=.985), and the interaction between the 3 factors (P=.997) were not significant.

Within the ferrule and no ferrule groups (F and Nf), fracture resistance was not significantly affected by post type, core, or crown type. However, without a ferrule, incisors restored with a metal crown presented significantly lower (P=.013) fracture

Table I. Mean buccal strain values (SDs) and results of Tukey HSD test (μS)

	F (Ferrule)		Nf (No Ferrule)	
Sum of Core Type	**Mc (Metal Crown)**	**Cc (Ceramic Crown)**	**Mc (Metal Crown)**	**Cc (Ceramic Crown)**
Cpc (cast post and core)	265.7 (50.4)^{A,a}	250.8 (92.8)^{A,a}	370.2 (90.3)^{A,a}	313.1 (101.4)^{A,a}
Gfr (glass fiber post/composite resin core)	297.2 (93.9)^{A,a}	236.4 (55.5)^{A,a}	560.6 (137.1)^{B,b}	281.1 (98.9)^{A,a}
Gfc (glass fiber post/fiber-reinforced core)	301.7 (82.2)^{A,a}	202.8 (75.9)^{A,a}	588.1 (96.8)^{B,b}	327.7 (59.3)^{A,a}

Different uppercase letters in vertical columns indicate significant differences; different lowercase letters in horizontal rows indicate significant differences; Tukey HSD test (P<.05).

Table II. Three-way ANOVA of buccal strain values

Source of Variation	*df*	Sum of Squares	Mean Square	F	*P*
Ferrule	1	327358	327358	41	<.001
Core type	2	33930	16965	2.1	.130
Crown	1	248012	248012	31.2	<.001
Ferrule × core type	2	37669	18835	2.4	.105
Ferrule × crown type	1	74260	74260	9.3	.004
Core type × crown type	2	64594	32297	4.1	.024
Ferrule × core type × crown type	2	20283	10141	1.3	.289
Error	48	381904	7956		
Total	60	7839132			
Corrected total	59	1188009			

Table III. Mean proximal strain values (SDs) and results of Tukey HSD test (μS)

	F (Ferrule)		Nf (No Ferrule)	
Core Type	Mc (Metal Crown)	Cc (Ceramic Crown)	Mc (Metal Crown)	Cc (Ceramic Crown)
Cpc (cast post and core)	80.0 (49.0)^{A,c}	52.2 (27.2)^{A,a}	90.8 (51.2)^{A,d}	70.7 (35.1)^{A,b}
Gfr (glass fiber post/composite resin core)	80.9 (43.3)^{A,c}	59.2 (19.8)^{A,a}	113.2 (53.7)^{B,d}	72.9 (19.2)^{A,b}
Gfc (glass fiber post/fiber-reinforced core)	69.2 (19.8)^{A,b}	51.2 (19.9)^{A,a}	130.7 (57.1)^{B,d}	88.8 (50.3)^{A,c}

Different uppercase letters in vertical columns indicate significant differences; different lowercase letters in horizontal rows indicate significant differences; Tukey HSD test (P<.05).

Table IV. Three-way ANOVA of proximal strain values

Source of Variation	*df*	Sum of Squares	Mean Square	Calculated F	*P*
Ferrule	1	10327	10327	6.1	.017
Core type	2	1205	602	0.359	.700
Crown	1	14548	14548	8.7	.005
Ferrule × core type	2	1288	644	0.384	.683
Ferrule × crown type	1	589	589	0.351	.556
Core type × crown type	2	1396	698	0.416	.662
Ferrule × core type × crown type	2	2123	1061	0.633	.535
Error	48	80485	1677		
Total	60	493312			
Corrected total	59	111962			

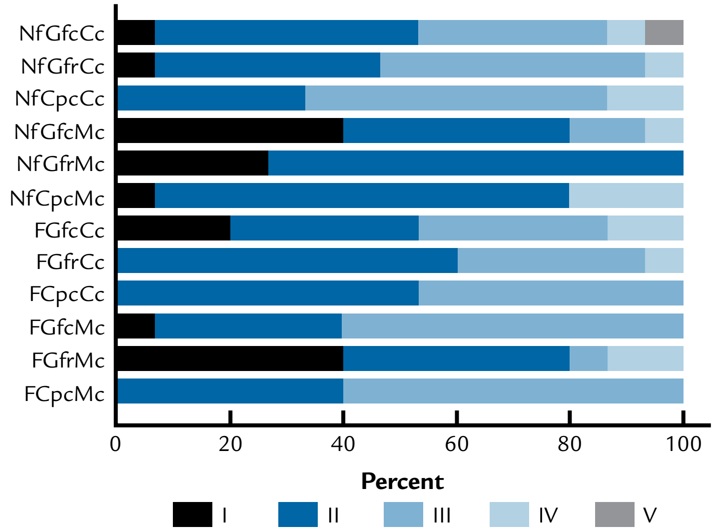
Table V. Mean fracture resistance values (SDs) and results of Tukey HSD test (μS)

Core Type	F (Ferrule)		Nf (No Ferrule)	
	Mc (Metal Crown)	Cc (Ceramic Crown)	Mc (Metal Crown)	Cc (Ceramic Crown)
Cpc (cast post and core)	902.9 (252.5)^{A,a}	910.1 (237.8)^{A,a}	656.2 (239.8)^{A,b}	796.3 (181.9)^{A,ab}
Gfr (glass fiber post/composite resin core)	910.4 (272.8)^{A,a}	919.9 (285.1)^{A,a}	570.0 (147.8)^{A,b}	712.7 (165.0)^{A,ab}
Gfc (glass fiber post/fiber-reinforced core)	919.3 (273.8)^{A,a}	945.6 (224.8)^{A,a}	572.0 (117.1)^{A,b}	719.5 (207.4)^{A,ab}

Different uppercase letters in vertical columns indicate significant differences; different lowercase letters in horizontal rows indicate significant differences; Tukey HSD test (*P*<.05).

Table VI. Three-way ANOVA of fracture resistance values

Source of Variation	*df*	Sum of Squares	Mean Square	Calculated F	*P*
Ferrule	1	2743676	2743676	55.0	<.001
Core type	2	46303	23152	0.465	.629
Crown	1	279977	279977	5.6	.004
Ferrule × core type	2	101215	50607	1.0	.364
Ferrule × crown type	1	187469	187469	3.8	.016
Core type × crown type	2	1491	746	0.015	.985
Ferrule × core type × crown type	2	344	172	0.003	.997
Error	168	8370642	49825		
Total	180	125373220			
Corrected total	179	11731117			



7 Fracture mode distribution.

resistance values, irrespective of core or post type.

Fracture mode distribution for the different groups is presented in Figure 7. Fracture in the crown, core, and/or cervical third of the root (modes I and II) was dominant (≥80%) in the groups with metal crowns and without ferrule (NfCpcMc, NfGfrMc, NfGfcMc), as well as in the group with ferrule, glass fiber post, and composite resin core (FGfrMc). Cast post-and-core groups (Cpc) generally showed low incidence of core fractures (mode I).

DISCUSSION

The null hypothesis that the mechanical behavior of anterior endodontically treated teeth would not be affected by the amount of the remaining tooth structure, nor by the type of post, core, and crown, was rejected. The mechanical integrity of the endodontically treated bovine incisors was affected by all evaluated factors. The interactions between various combinations of these factors were assessed by measuring deformations (strains) and fracture strengths, and by observing failure modes.[24,29] To have comparable conditions between the test specimens, this study used bovine incisors of animals of similar age instead of human incisors. Human incisors have a greater variability in size and morphology, and are therefore more difficult to standardize. Bovine dentin is often used for in vitro tests, and is generally considered similar to human dentin in composition and geometric root configuration.[34-36] The greater availability of bovine teeth made it possible to standardize specimen size and shape.[2,24,29] Standardization was essential for obtaining comparable results because deformation and fracture load depend on geometry.

The incisors in this study were loaded statically in nondestructive and destructive tests. During oral function, teeth are subjected to dynamic masticatory and thermal loading. This subcritical loading may result in a slow process of incremental structural degradation, often referred to as "fatigue."[15] The strain measured during the nondestructive tests in this study can be regarded as an indication of the repetitive deformation that roots undergo during functioning, resulting in such structural fatigue.[30] The current results show that the strain gauges attached to the buccal and proximal surfaces could detect differences between the various restorative procedures. For example, strain values observed at the proximal surface indicated that the presence of a 2.0-mm ferrule produced changes in deformation behavior of the restorative complex (Table III). Similar observations have been reported by Santos-Filho et al.[24]

Measuring the deformation behavior preceding fracture may contribute to a better understanding of the entire fracture process, from initiation to ultimate rupture.[29] The strain gauges were attached near sites where fractures were expected to start. The proximal strain gauges were oriented perpendicular to the longitudinal root axis because this strain component can initiate cracks that lead to catastrophic fractures.[24] It was found that, in general, lower strain values (both buccal and proximal) corresponded with higher fracture resistance (R=0.85). The correlation was lower in the presence of a ferrule (R=0.63) and higher without a ferrule (R=0.90).

The results of the present study confirmed that the presence of a 2.0-mm ferrule increased the fracture resistance of the endodontically treated incisors, irrespective of crown, core, or post type. This may be attributed to an improved stress distribution in the root structure. Pierrisnard et al[28] showed that a 2.0-mm ferrule in teeth restored with metal crowns reduced the level of stress concentration in dentin for different metal and nonmetal post systems. Although proximal strains were consistently lower in combination with an alumina-reinforced ceramic crown, buccal strain and fracture resistance values were not affected in the presence of the ferrule. Thus, changes in stiffness associated with post and core materials did not appear to significantly influence the strain values and fracture resistance as long as sufficient dentin structure remained. The lower proximal strains measured for the ceramic crowns may be due to improved adhesion with resin cement. This has also been observed in thermomechanical fatigue studies.[27] However, these results may change, since some degree of bonding deterioration can occur with aging.

Although most studies agree that ferrules improve fracture strength, sufficient coronal structure is often absent in clinical situations.[10] Groups without a ferrule restored with ceramic crowns showed higher fracture resistance and lower strains than those restored with metal crowns. The use of ceramic crowns seemed to nearly overcome the disadvantage of ferrule absence, and in these instances, the influence of post type on the buccal strains (Table I) and the influence of post type on fracture resistance (Table V) were not significantly different. Only the proximal strains were significantly higher for teeth with ceramic crowns and without ferrule (Table III). However, although the differences in buccal strains and fracture resistance were not statistically significant, the mean values for groups restored with ceramic crowns without ferrule were still consistently lower than those with ferrule, by approximately 20%. The higher proximal strain values, located where fractures are thought to initiate, may have been indicative of the lower fracture resistance. Furthermore, it should be noted that the fractures in groups for which metal crowns were used in restorations without a ferrule were found to be less serious (predominant fracture modes I and II) compared to ceramic crowns (Fig. 6).

In the present study, no critical differences in deformation and fracture performance were found that could be exclusively attributed to the post or core system tested. The more recently introduced fiber-reinforced core did not show improvement in the fracture resistance or reduction of the strain values. According to the manufacturer, this system was developed to allow the use of prefabricated posts in a wide range of teeth, including those without coronal tooth structure. The results of the present study did not prove the efficacy of this product, perhaps because the integration between the fiber-reinforced core and the post coronal portion was determined by the properties of the resin cement layer. Future studies should investigate the integration between a fiber-reinforced core and glass fiber post. For all post-and-core systems, fracture resistance was primarily determined by ferrule presence and crown type. Only strain gauge measurements detected some significant differences between the various post-and-core combinations, especially at the proximal surface. The general trend was lower strains and higher fracture resistance for cast post and cores compared to systems with glass fiber posts, which is consistent with previous findings.[23] This mechanical response has been explained by the stiffness of post-and-core systems; this increased stiffness reduced the load on the dentin, resulting in reduced stress levels in this tissue.[28] However, the associated tendency for more disastrous fracture types with stiff cast post-and-core systems[17] could not be verified from the fracture modes recorded in this study (Fig. 7).

In summary, it was demonstrated that strain gauge measurements could detect subtle differences in mechanical response even when fracture resistance results could not. The strain measurements generally correlated well with the fracture behavior of the various combinations of tooth restoration systems. Using the in vitro deformation and fracture measurements, this study confirmed the hypothesis that the mechanical behavior of severely compromised, endodontically treated incisors was primarily determined by the presence of a ferrule and by crown type. The effects of post system and core were secondary. It can be concluded that conservation of healthy tooth structure and the selection of a suitable restorative system are crucial to ensure adequate strain and fracture resistance for the improved prognosis of these severely compromised teeth.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. The presence of a ferrule is a determining factor in the strain distribution and fracture resistance of endodontically treated incisors restored with metal crowns, irrespective of the core type.

2. For metal crown restorations with no ferrule, cast post and cores showed better biomechanical performance than glass fiber posts.

3. With respect to biomechanical behavior, alumina-reinforced ceramic crown restorations were not influenced by the core type.

4. The presence of a ferrule was essential for the use of glass fiber posts in combination with metal crown restorations.

5. The core did not influence the biomechanical behavior of endodontically treated incisors with a 2.0-mm ferrule, irrespective of the crown type.

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