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Effect of Ferrule Thickness on Fracture Resistance of Teeth Restored With a Glass Fiber Post or Cast Post

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Clinical Relevance

A tooth without a ferrule presented more favorable failures than with a 1-mm-thick ferrule when restored with a cast post and core, despite an increased fracture resistance. The findings support the use of a glass fiber post.

SUMMARY

Purpose: To investigate the influence of ferrule thickness on fracture resistance after mechanical cycling of teeth restored with different intracanal posts.

Methods and Materials: One hundred twenty bovine incisor teeth were randomized into six study groups, based on the intracanal post used (fiber post or cast post and core) and the presence and thickness of a ferrule (without ferrule, presence of 0.5-mm or 1-mm-thick ferrule, retaining unaltered 2-mm ferrule height). The root posts and the metal crowns were cemented using an adhesive cement. The samples were subjected to mechanical cycling (at 37°C, 45°, 130 N, 2.2 Hz, and 2×10^6 pulses). Afterward, they were subjected to a fracture load test at a speed of 0.5 mm/min and on a 45° slope until failure occurred. The failures were classified as favorable or unfavorable. The fracture resistance data were analyzed with two-way analysis of variance and Tukey test. The chi-square test was used to analyze the pattern of failure.

Results: When considering the cast post and core, the 1-mm ferrule thickness group pre-

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sented a higher resistance to fracture than did the group in which a ferrule was not used (p=0.001). When using a glass fiber post, the groups showed no differences in fracture resistance. Overall, 96.7% of the specimens survived the mechanical cycling. Of the fractures, 58.6% of the fractures were unfavorable, while 41.6% were favorable.

Conclusions: A thicker ferrule statistically increased the fracture resistance only for cast post and core when it was at least 1 mm thick, despite causing more unfavorable failures. Thus, ferrule thickness should be considered when choosing different intracanal posts, to reduce the occurrence of unfavorable failures. In the absence of a ferrule, the use of a cast post and core presents more favorable failures, and in the presence of a 1-mm-thick ferrule, the use of a glass fiber post seems to be the best clinical decision.

INTRODUCTION

The prognosis of endodontically treated teeth depends on several factors, such as adequate coronal reconstruction,[1] tooth position in the dental arch, type of final restoration, post length and thickness, and the presence of a ferrule.[2] A ferrule is composed of parallel walls of dentin from the crown's margin extending coronally to the fractured part of the tooth (see Figure 1).[2,3] Fabricating a crown around the remaining structures and generating a ferrule effect[2-4] may reduce intraradicular stress and thus the incidence of fractures.[5]

The clinical outcome is significantly influenced by the amount of residual coronal dentin,[6] and the existing literature extensively describes the importance of having adequate ferrule height.[7] Studies have demonstrated that a minimum ferrule height of 1.5-2 mm shows improvement in the longevity of endodontically treated teeth restored with post and core[2,7,8] and also provides better fracture resistance.[7,9]

The influence of ferrule thickness on clinical outcome is also a topic that needs to be explored further.[7] The amount of residual axial tooth structure to be significant in fracture resistance has been reported in the literature[7,10,11]; however, some reports have excluded the width of shoulder preparation and crown margin as significant factors. The shoulder preparation could compromise the thickness of the buccal dentinal wall when esthetics require more invasive preparations at the margin or because of existing carious lesions.[7] For instance, ceramic restorations commonly require that the remaining dentin thickness at the margins of the preparations are reduced by at least 1.5 mm to achieve desirable esthetics.[7,12]

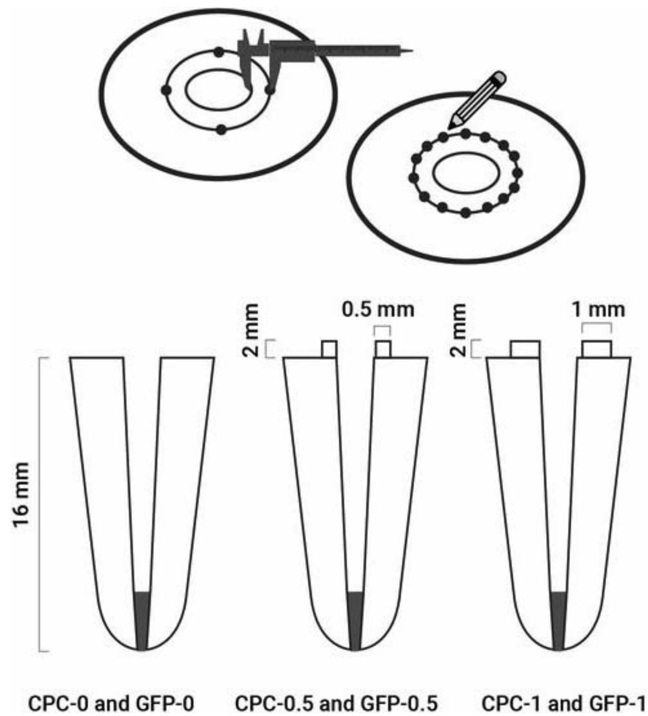


Figure 1. *Schematic diagram of the marking of the ferrule thickness and experimental groups.*

Although it has been accepted clinically that a ferrule thickness of 1 mm is considered very thin,[7] there are only a few studies in the literature reporting the effect of remaining coronal thickness on the mechanical behavior of endodontically treated teeth.[13,14] Tjan and Whang[13] reported that there was no significant difference among the groups that had remaining buccal dentin of varying thickness of 1 mm, 1 mm with a 60° bevel, 2 mm, and 3 mm. However, a dentin thickness of 1 mm resulted in a higher incidence of failure due to fracture rather than cement failure.[13] In addition, Joseph and Ramachandran[14] studied the effectiveness of incorporating the thickness of coronal dentin and concluded that fracture resistance increased in the case of 2-mm-thick remaining dentin.[14] On the other hand, there are no studies in the literature evaluating the effect of 0.5-mm ferrule thickness on resistance to fracture.[7]

Thus, the objective of this research was to evaluate the influence of the remaining coronal thickness (without ferrule, 0.5-mm thickness, and 1-mm

Table 1: *Study Design*

Study Factors		Group Code
Kind of Root Posts	Thickness of Ferrule	
Glass fiber post	No ferrule	GFP-0
	Ferrule with a height of 2 mm and a thickness of 0.5 mm	GFP-0.5
	Ferrule with a height of 2 mm and a thickness of 1 mm	GFP-1
Cast post and core	No ferrule	CPC-0
	Ferrule with a height of 2 mm and a thickness of 0.5 mm	CPC-0.5
	Ferrule with a height of 2 mm and a thickness of 1 mm	CPC-1

thickness) on the resistance to fracture of endodontically treated teeth with a glass-fiber post or cast post and core. The null hypothesis was that ferrule thickness has no influence on the fracture resistance of endodontically treated teeth restored with different intracanal posts after mechanical cycling and fracture load test.

METHODS AND MATERIALS

Selection of Specimens

The number of teeth to be used in the present research was determined by performing a sample calculation with the OpenEpi 3.01 program,[15] with the parameters used previously in a study by Wandscher and others.[16] The power of the study was defined as 80%, with a level of significance of 0.05, identifying the need for 15 teeth per group. However, because of the variability of bovine teeth, radicular anatomy, and possible variability in the preparation of the ferrule, 20 teeth were allocated to each group.

One hundred twenty bovine incisor teeth were selected and analyzed for possible fractures, cracks, and fissures, with the aid of a loupe (4× magnifying, EyeMag Pro S, Carl Zeiss, Gottingen, Germany). Afterward, the selected teeth were randomized through the website random.org into six groups (n=20 in each) based on the post type (glass fiber post [GFP] or cast post and core [CPC]) and features of the ferrule (Table 1).

Thereafter, the coronal portion of each tooth was sectioned at a distance of 16 mm (in the absence of a ferrule, CPC-0 and GFP-0) or 18 mm (in the presence of a 2-mm-high ferrule, with varying thickness, CPC-0.5, CPC-1, GFP-0.5, and GFP-1) from the root apex, resulting in a standard height. All procedures were performed by two trained researchers.

To avoid differences in tooth size among the groups, the mesiodistal and vestibular-lingual dimensions of the teeth were measured with the aid of digital calipers (Starrett 727, Starrett, Itu, São Paulo, Brazil), and the measurements were tabulated. The data were verified to be normally distributed. Subsequently, a one-way analysis of variance (ANOVA) was performed to verify differences in the measured dimensions between the groups. No statistically significant difference (α=0.05) in the dimensions of the teeth could be detected.

Periodontal Ligament Confection and Endodontic Treatment

To simulate the periodontal ligament and the biological space, the roots were coated with a layer of wax (Lysanda, São Paulo, Brazil) of 0.3-mm thickness (measured by digital calipers; Starrett 727, Itu). For this purpose, the wax was liquefied in a container at a standard temperature of 70°C, and each tooth was placed inside up to 3 mm below the most coronal portion of the root. Then, each tooth was embedded in a polyvinyl chloride cylinder (height of 20 mm and diameter of 25 mm) with self-cured acrylic resin (VIPI Flash, VIPI, Pirassununga, São Paulo, Brazil) up to 3 mm below the most coronal portion of the root, simulating the biologic space. Afterward, the tooth was removed from the acrylic resin and the wax was removed, creating a space corresponding to the periodontal ligament. Subsequently, the impression material was manipulated as recommended by the manufacturer and inserted into the artificial alveolus. The tooth was placed into its respective alveolus, and excess impression material was removed; thus, the elastomeric material (Impregum F, 3M-ESPE, Seefeld, Germany) mimicked the periodontal ligament.[17]

Afterward, the root was prepared using the step-back technique, using second- and third-series endodontic files (Dentsply-Maillefer, Ballaigues, Switzerland) and Nos. 3, 4, and 5 Gates-Glidden burs (Dentsply-Maillefer). The specimens were filled with AH plus sealer (Dentsply-Maillefer), and the root canals were obturated with gutta-percha cones (Dentsply-Maillefer). The compaction technique used was cold lateral condensation with a force of 2000*g* standardized through a digital scale.[18] The specimens were stored in deionized water at 37°C for 24 hours.

Intracanal Preparation for Post Seat

A post space (cementation length) of 12 mm was prepared for the groups without ferrule (CPC-0, GFP-0), and 14 mm preparation was used for the groups with ferrule (GFP-0.5, GFP-1, CPC-0.5, CPC-1). For the GFP-0, GFP-0.5, and GFP-1 groups, the preparation was initially performed by No. 4 Largo burs (Dentsply Maillefer) and finished with standardized drills of the Whitepost DC No. 2 fiberglass post system (FGM, Joinville, Brazil). For the CPC-0, CPC-0.5, and CPC-1 groups, the post space was prepared using Nos. 3, 4, and 5 Largo burs (Dentsply Maillefer).

Preparation of Ferrule

The ferrules in the GFP-0.5, GFP-1, CPC-0.5, and CPC-1 groups were manually prepared with a diamond bur (No. 3216, KG Sorensen, Barueri, Brazil) using a high-speed hand piece (Extra Torque 605C; Kavo do Brasil, Joinville, Brazil) with water spray cooling, resulting in the corresponding thickness of each group and standard height of 2 mm. For this, the thickness and height to be removed were marked with graphite with the aid of a digital caliper (Starrett 727, Itu; Figure 1).

Production of the Cast Post and Cores

The standards for the cast post and core were obtained by molding the root canals with chemically activated acrylic resin Bosworth Trim Plus (Bosworth Company, Skokie, IL, USA) and prefabricated plastic posts (Pinjet, Ângelus, Londrina, Paraná, Brazil). For preparation of the coronal part of the core, acetic matrices were used.

Resin patterns were handed over to a commercial laboratory for casting. Next, the cast post and cores were evaluated for adaptation.

Cementation of the Posts and Crowns

Prior to post cementation, the intracanal surfaces of the cast post and cores were air-abraded with aluminum oxide particles (110 μm, pressure 2.8 bars, 10-mm distance and 15 seconds; Blue, São José do Rio Preto, Brazil).

For the glass fiber post groups and cast post and core groups, 7 mm of the coronal portion of the post was retained. All surfaces of each glass fiber post were cleaned with 70% alcohol. Next, a silane coupling agent (Prosil, FGM, Joinville, Santa Catarina, Brazil) was applied to each post, and the solvent was allowed to evaporate for five minutes.

All root posts were cemented using the same procedures: the root canal and the coronal portions were prepared using 37% phosphoric acid (Condac 37, FGM), and the adhesive Ambar (FGM) was applied according to the manufacturer's guidelines. Finally, the posts were cemented with dual-cure resin cement (Allcem, FGM), which was also manipulated as recommended by the manufacturer.

The cores (for glass fiber post samples) were fabricated with a composite resin (Opallis, FGM) with acetic matrix (identical to that used for the CPC-0 groups). The matrix was filled with increments of composite resin and adapted over the coronal portion of the post. Afterward, the matrices were sectioned and the composite resin was photo activated (1200 mW/cm^2; Radiical, SDI, Victoria, Australia) on each side of the tooth for 10 seconds.

For all groups, metallic full crowns (Ni-Cr alloy; Wirona light, Bego, Goldschlagerei, Germany) were prepared with standardized shape and dimensions, according to the anatomy of a maxillary canine. After that, the crowns were evaluated and air-abraded with aluminum oxide (110 μm, pressure 2.8 bars, 10-mm distance, and 15 seconds).

Before the crowns were cemented, they were cleaned with absolute alcohol. The dentin and core (composite and metal) surfaces were etched with 37% phosphoric acid for 15 seconds, followed by rinsing with air-water spray and drying with absorbent paper, and the adhesive Ambar (FGM) was applied according to the manufacturer's guidelines. The full-metal crowns were cemented with a dual-cure resin cement (Allcem, FGM), according to the manufacturer's guidelines. Next, a 5-kg load was applied on each metal crown by means of a static press, during cementation. Excess cement was removed after three minutes, and photo-activation was carried out (1200 mW/cm^2, Radiical, SDI) on each side of the tooth for 10 seconds. The samples were stored for 24 hours before testing.

Mechanical Cycling

The specimens were subjected to mechanical cycling (Erios ER 3000, São Paulo, Brazil) for the aging, with the following protocol: 2.2-Hz frequency, 2 million load pulses from 0 N to 130 N, immersion in water at 37°C temperature, and piston at a 45° angle with respect to the long axis of the root and at 2 mm distance from the lingual incisal edge. Thus, in this trial, approximately two years of clinical service was simulated, since Wiskott and others[19] determined that 1 million cycles correspond to one year of service.

Fracture Load Test

After mechanical cycling, the specimens were analyzed for the presence of fractures, and those that did

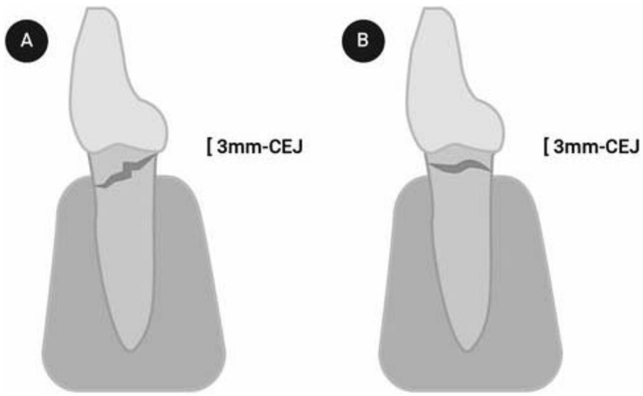


Figure 2. *Schematic diagram of failures. (A) Failure unfavorable. (B) Failure favorable.*

not present with cracks were subjected to the fracture load test in a universal test machine (DL 2000, Emic, São José dos Pinhais, Brazil). Each sample was positioned on a fixed metal device and aligned at a 45° angle, under 0.5 mm/min until failure occurred. The cylindrical metallic tip (diameter 0.8 mm) attached to the load cell (1000 kN) was applied as a lingual load (2 mm from the lingual incisal edge). A load point at which the force resulted in root fracture, post curvature, or core and post displacement was defined as the threshold of failure.

Failure Analysis

The roots were stained superficially with hydrographic pens (Blue overhead marker, Faber-Castell, São Carlos, Brazil), after the fracture load test. The excess ink was then removed with cotton and 70% alcohol, and the specimens were visualized with a stereomicroscope at 10× magnification (Stereomicroscope Discovery V20; Carl Zeiss, Germany). The failures were classified as favorable (ie, above the 3-mm limit of the acrylic resin, up to the limit of the simulated cemento-enamel junction [CEJ]) and unfavorable (ie, below the aforementioned limit, below the CEJ; Figure 2). Fractured specimens were transversely sectioned in a cutting machine (Isomet 1000 Precision Saw, Buehler, Lake Bluff, IL, USA) with a diamond saw, making it possible to inspect the crack and its features.

Data Analysis

Using the Shapiro-Wilk test, the fracture load data were analyzed for their distribution, while their homogeneity was analyzed using the Levene test. They were found to have a homogeneous and normal distribution ($p>0.05$). Then, the fracture load data were submitted to two-way ANOVA and Tukey tests ($\alpha=0.05$). In addition, the chi-square test was used to analyze the association between the different patterns of failure and the different groups.

RESULTS

Mechanical Cycling

In total, 96.7% of the specimens survived mechanical cycling. In the GFP-0 group, two failures occurred, one being favorable, presenting a crack at the vestibular region and detachment of the crown from the lingual region, and one unfavorable, with cracks at the proximal and lingual regions, besides displacement of the crown from the lingual region. The unfavorable fracture occurred in the GFP-0.5 group with cracks at the proximal region and displacement of the crown from the lingual region. In the CPC-0.5 group, only an adhesive failure was observed in the lingual region. In the CPC-0, GFP-1, and CPC-1 groups, there were no failures during cycling (Table 2).

Fracture Load

Table 3 shows the fracture load data (N). The Tukey test showed a significant difference between the groups CPC-0 and CPC-1 ($p=0.001$). The other groups did not demonstrate significant differences.

Failure Analysis

Table 2 enumerates the failures that occurred during the fracture load test and mechanical cycling, in addition to the location of fracture. Of the fractures, 58.6% of the fractures were unfavorable, while 41.6% were favorable. In the groups that used a glass fiber post, the GFP-1 group showed the most favorable failures (60.0%), while among the groups that used the cast post and core, the CPC-0 group presented more favorable failures (80.0%). After the fracture load test, the surface that presented the most cracks in the radicular third was the distal surface, followed by the mesial. Furthermore, displacement of the lingual portion of the crown occurred in 82% of the specimens.

The pattern of failure was analyzed using the chi-square test (Table 4). When comparing groups that used the same type of post but different thicknesses of the ferrule, it was observed that in the glass fiber post groups, only the GFP-0.5 and GPF-1 groups showed a statistically significant difference between them ($p=0.01$); among the groups that used a cast post and core, there was a statistical difference between the CPC-0 and CPC-0.5 groups ($p=0.001$) and between the CPC-0 and CPC-1 ($p=0.001$) groups. On the other hand, when comparing groups

Table 2: *Qualitative Evaluation of Failures After Mechanical Cycling and Fracture Load Test*

	Study Group, n (%)						
	GFP-0	GFP-0.5	GFP-1	CPC-0	CPC-0.5	CPC-1	Total
Failures during mechanical cycling							
Pattern of failure							
Favorable	1	—	—	—	1	—	2
Unfavorable	1	1	—	—	—	—	2
Failure place							
Crown displacement (lingual)	2	1	—	—	—	—	3
Mesial crack	1	1	—	—	—	—	3
Buccal crack	1	—	—	—	—	—	1
Distal crack	1	1	—	—	—	—	2
Lingual crack	1	—	—	—	—	—	1
Fracture in the post	—	—	—	—	—	—	—
Crown, core, post pull out	—	—	—	—	1	—	1
Failures after fracture load							
Pattern of failure							
Favorable	8 (44.4)	4 (21.1)	12 (60.0)	16 (80.0)	4 (21.1)	4 (20.0)	48 (41.4)
Unfavorable	10 (55.6)	15 (78.9)	8 (40.0)	4 (20.0)	15 (78.9)	16 (80.0)	68 (58.6)
Failure place							
Crown displacement (lingual)	17	15	19	14	16	17	98
Mesial crack	11	16	15	10	15	16	83
Buccal crack	8	3	10	9	8	15	53
Distal crack	13	16	16	6	16	18	85
Lingual crack	1	—	—	1	—	3	5
Fracture in the post	—	—	—		—	1	1
Crown, core, post pull out	2	1	—	5	3	3	14
Failure mode							
Mesiodistal	10	16	15	6	11	16	
Buccolingual	—	—	—	—	—	1	

with different types of posts but the same ferrule thickness, the groups with a 0.5-mm-thick ferrule presented no differences among them, while the other groups presented differences.

DISCUSSION

The present study showed that remaining coronal thickness affected the fracture resistance of endodontically treated teeth that were restored using a cast post and core. Thus, the null hypothesis was rejected.

The mechanical cycling of the specimens was performed by simulating an aging condition close to a real-life situation. Applying 2 million cycles simulated approximately two years of clinical service.[19] We found that 96.7% of the specimens survived the mechanical cycling. Two failures in the GFP-0 group and one in the GFP-0.5 group were reported on analysis of the failures that occurred following mechanical cycling in the groups that used glass fiber posts. However, the group with the highest ferrule thickness (GFP-1) exhibited no failure, which corroborates that the greater the

Table 3: *Mean (± Standard Deviation) of the Results of Fracture Load (N) Test and Tukey's Test[a]*

Post	Thickness of Ferrule		
	Without Ferrule	0.5 mm	1 mm
Glass fiber post	352.66 ± 219.02 aA	462.39 ± 272.65 aA	474.30 ± 219.67 aA
Cast post and core	339.04 ± 153.78 aB	483.69 ± 342.77 aAB	575.72 ± 214.34 aA

[a] *Uppercase letters compare groups with the same intracanal post but different ferrule thickness (rows). Lowercase letters compare groups with the same ferrule thickness but different intracanal post (column).*

Table 4: *Association Between Groups and Pattern of Failures, Chi-Square Test*[a]

Pattern of Failure	Thickness of Ferrule, %		
	Without Ferrule	0.5 mm	1 mm
Glass fiber post	ABb	Ba	Aa
Favorable	44.44	20	60
Unfavorable	55.56	80	40
Cast post and core	Aa	Ba	Bb
Favorable	80	21.05	20
Unfavorable	20	78.95	80

[a] *Uppercase letters compare groups with the same intracanal post but different ferrule thickness. Lowercase letters compare groups with the same ferrule thickness but different intracanal post.*

ferrule thickness, the higher the chance of longer tooth survival without failure.

The CPC-0 and CPC-1 groups presented a significant difference in the fracture resistance test, since the CPC-1 group had a higher value of fracture resistance, followed by the CPC-0.5 group and, finally, the CPC-0 group. However, there was no significant difference when the thickness varied by only 0.5 mm (CPC-0 for CPC-0.5; CPC-0.5 for CPC-1; Table 3). This can be explained by the small increase in ferrule thickness (0.5 mm) because clinically, the coronal walls are considered to be very thin when they are less than 1-mm thick.[7] Furthermore, the number of unfavorable failures also increased when the ferrule thickness reached 0.5 mm or 1 mm (Table 2). The possible reason for this was an increase in the fracture resistance with a thicker ferrule. Moreover, an increase in unfavorable failures can also be explained by the high modulus of elasticity of nickel-chromium (Ni-Cr) that can concentrate stresses through the post and core into the walls of the root canals.[20,21]

On analysis of the groups that used glass fiber posts, no increase in fracture resistance was found with increasing ferrule thickness (Table 3). This may be due to better stress distribution by the glass fiber post as compared with the cast post and core.[22] In accordance with these results, in a classic study by Sorensen and Engelman,[23] it was shown that the axial width of the tooth at the crown margin did not significantly increase the fracture resistance or alter the failure threshold. In addition, a clinical study by Mancebo and others[24] demonstrated that endodontically treated teeth with a ferrule, that were restored with glass fiber posts, showed better clinical survival after 3 years of clinical service compared with nonferrule teeth. In agreement with Macebo and others,[24] in this study, the failures were more favorable in the endodontically treated teeth restored with a glass fiber post and 1-mm-thick ferrules when compared with teeth treated endodontically and restored with glass fiber posts without ferrules.

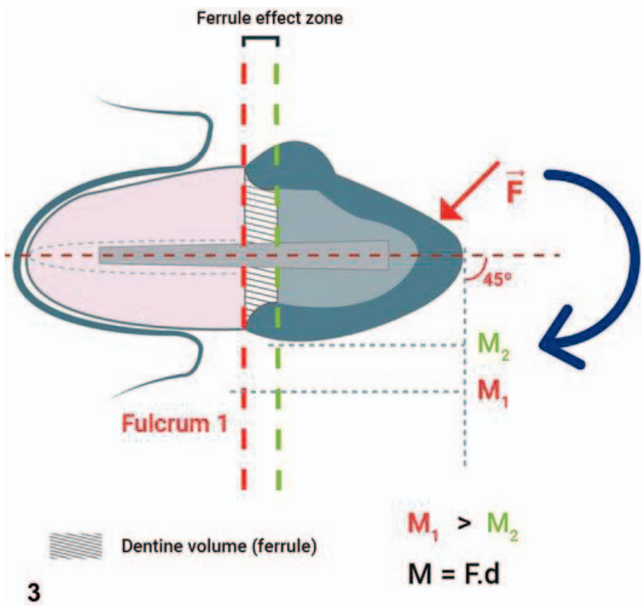
The chi-square test (Table 4), using the proportions of failure pattern in each group, was performed to determine whether there was a difference in the failure mode between different types of posts and ferrule thicknesses. When the specimen had no ferrule—in the GFP-0 (44.4% favorable failures) and CPC-0 groups (80.0% favorable failures; $p=0.02$)—the cast post and core could be used because there were more favorable failures. When the specimen had a 0.5-mm-thick ferrule, either of the post types could be used because there was no statistically significant difference between their failure patterns ($p=0.77$). In contrast, with a 1-mm-thick ferrule, a fiber post (60.0% favorable failures) will be more suitable than a cast post and core (20.0% favorable failures; $p=0.01$).

According to Santos and others,[20] in order to choose a suitable technique to restore endodontically treated maxillary incisor teeth, we must take into account the amount of dental structure remaining and the esthetic and functional considerations. Furthermore, there is evidence in the literature supporting the clinical choice of glass fiber post when there is more remnant coronal structure and cast post and core when there is none.[22,25,26] In this study, we observed that the CPC-0 subgroup had a higher percentage of favorable failures than the GFP-0 subgroup, and the GFP-1 subgroup had more favorable failures than the CPC-1 subgroup (Table 4), which agree with the results reported in the literature. Figure 1 shows that the teeth without any coronal remnant could probably suffer from more bending than those with some remnant. It is stated that the fiber post concentrated stresses at the cervical level[27]; hence, the stress distribution to dentin in this region is higher. However, when the ferrule effect exists, the fiber post presents with less tendency to bend.

Recently, Wandscher and others analyzed flared roots restored with different types of posts that fractured after cyclic and static loading (demonstrated by means of fractographic analysis) and found that the final fracture was a consequence of tensile, compression, and shear stresses.[16] Taking into consideration the interpretation of the fractured surface, failure analysis revealed the direction of crack propagation, thus recognizing the origin or cause of failure.[28] The origin of the fracture may be a location, a specific flaw, or an irregularity. The nature of loading (tensile, bending, shear, torsion, and fatigue), microstructure of the material, environment factors, and stress concentrators indicate the appearance of marks at the location of the origin of the failure.[29] A few studies of endodontically treated teeth restored with posts present a detailed analysis of the fractured specimens. Therefore, only a few studies have evaluated in detail the fractured surfaces of teeth with remaining coronal structure (the ferrule effect). However, those results strongly suggest that the remaining coronal thickness might influence the stress distribution on the tooth/post/crown, consequently affecting its fracture resistance and the mode of fracture.

In relation to the failure pattern, it is observed that the roots fractured at similar rates (Table 2) as those in the study by Wandscher and others,[16] presenting mesiodistal cracks independent of the type of post used. This feature is a consequence of the loading mode of the specimens (45°). Biomechanical studies demonstrated that restored teeth subjected to oblique loads suffered tensile (lingual surface) and compression (buccal surface) forces.[16,30,31] These tensions are maximal in the external portions (lingual and vestibular) and minimal in the center of the restorative set (root canal). The authors stated that a sequence of events led to the final fracture, such as shear stresses on the post-dentin adhesive interface that caused decementation of the assembly (crown displacement); thus, the post becomes loose in the canal, no longer acting as a unique structure and breaking on the buccal wall due to higher compressive stress.

In the current study, it was observed that the presence of the ferrule effect on a restored tooth with a post altered the arrangement of the forces acting on the restored tooth (without ferrule effect vs with ferrule effect groups). A tooth with a cervical ferrule presents a coronal displacement of the fulcrum line, decreasing the effect of flexion (bending moment)[32] and protecting the specimen (Figure 3). This fact explains why teeth with a ferrule effect present a higher loading fracture.



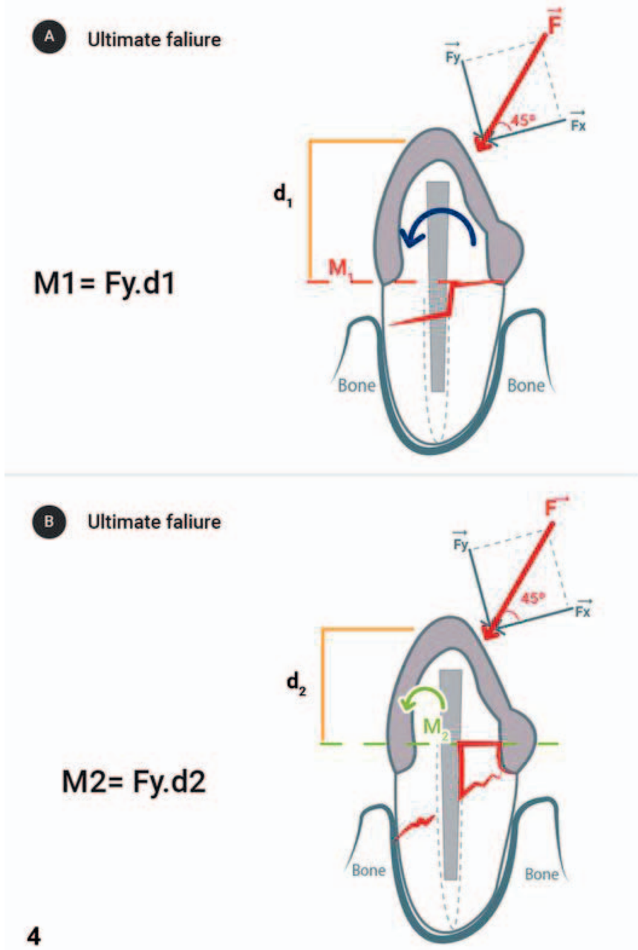


Figure 3. *Schematic representation of a restored tooth with a post subjected to an oblique force. $\vec{F}$: force exerted on the specimen (45°); fulcrum 1: fulcrum formed when there is no ferrule present in the specimen (GFP-0 and CPC-0 groups); fulcrum 2: fulcrum formed when there is presence of ferrule in the specimen (groups GFP-0.5, GFP-1, CPC-0.5 and CPC-1). M: bending moment (measured by multiplying the force applied by the distance between the point of application of the load and the fulcrum line); F: applied force; D: distance from the point of application of the load to the fulcrum line; M1: bending moment referring to the fulcrum 1; M2: bending moment relative to fulcrum 2; dentine volume: volume of coronary remaining present in specimens with the presence of ferrule.*

Figure 4. *(A): Specimens of the glass fiber post group or cast post and core group without a ferrule. (B): Specimens of the glass fiber post group or cast post and core group with a ferrule. Schematic drawing of the ultimate fracture without and with ferrule specimens ($\vec{F}$: force exerted on the specimen (45°); $\vec{F}_y$: vertical component of F; $\vec{F}_x$: horizontal component of F; d1: distance from the point of application of the load to the specimen; M1: bending moment of the specimen, red line).*

Comparing the groups with and without a ferrule effect, some differences in the failure pattern were observed (Figure 4). The nonferrule specimen presented with an adhesive failure between the crown and root (lingual surface), followed by a crack into the canal that finished on the buccal root dentin (Figure 4A). In contrast, the ferruled specimen presented with the same adhesive failure (crown/root) with a crack starting on the prosthetic shoulder into the canal (Figure 4B). The presence of the ferrule between the post and crown created a lever arm due to the bending movement (Figure 4). Therefore, it is possible to conclude that this feature protected the restored assembly. In addition, despite a nonstatistical difference between the groups, we concluded that the greater the thickness of the ferrule, the greater was the lever arm and fracture load. Moreover, some studies showed that the presence of a ferrule of 1.5 to 2 mm height was more important for fracture resistance than the post type or post design.[9,33,34]

Studies evaluating the fracture load of endodontically treated teeth restored with posts and tested *in vitro* presented higher values of fracture than the probability of the load to failure clinically; consequently a large standard deviation was obtained (Table 2).[31,35] Thus, new studies applying fatigue tests (such as staircase or step-stress approaches) should be conducted to predict the fatigue behavior of the restored roots. Furthermore, other factors such as loading direction, pH alterations, humidity, and temperature were difficult to simulate in *in vitro* tests. Further studies should be performed to develop methods or techniques that allow a detailed analysis of the fractured surface of endodontically treated teeth restored with posts.

CONCLUSIONS

- The fracture resistance increased statistically only when a ferrule thickness of 1 mm was present for the cast post and core.
- The use of a cast post and core without ferrule presents a lower occurrence of unfavorable failures. For teeth with a 0.5-mm-thick ferrule, both cast post and core and fiber post were associated with a similar percentage of unfavorable failures. For teeth with a 1-mm-thick ferrule, the use of the fiber post could be the appropriate clinical decision.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local oversight committee guidelines and policies of the Federal University of Santa Maria. The approval code for this study is 042272.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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