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Preliminary Results of the Survival and Fracture Load of Roots Restored With Intracanal Posts: Weakened vs Nonweakened Roots

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Clinical Relevance

When restoring roots with an adequate quantity of dental tissue, a cast post and core or fiber post may be used. But when weakened roots are being restored, fiber posts with a wider cervical emergence diameter appear to be the best clinical solution, even though the clinical prognosis is doubtful.

SUMMARY

Purpose: **To evaluate the fracture load and survival rate of weakened and non-weakened roots restored with different intracanal posts.**

Methods: **Eighty teeth (16 mm) were prepared to a length of 10 mm with a custom drill. Fifty roots were weakened with a tapered diamond drill, and 30 roots were not. The specimens were embedded with acrylic resin up to 3 mm from the coronal aspect, and the periodontal ligament was simulated. The 50 weakened roots were restored with (n=10) CPC-gold (cast post and core made of gold alloy), CPC-Ni (cast post and core made of Ni-Cr alloy), FP (glass fiber posts), FP-W (glass fiber posts with a wider coronal diameter), and FP-CR (fiber posts relined with composite resin). The 30 nonweakened roots were restored with (n=10) CPC-gold, CPC-Ni, and FP. All of the posts were adhesively cemented. All of the specimens were mechanically cycled (37°C, 45°, 130 N, 2.2 Hz, and 1.5 million pulses) and evaluated after every 5 × 10^4 cycles to evaluate the presence of cracks as a primary outcome (event). The specimens that survived cycling were subjected to a fracture load test (load application on the palatal aspect at a 45° inclination). Failure mode was classified as favorable (above the simulated bone level) and catastrophic (below the simulated bone level). Survival rates were estimated using the Kaplan-Meier method. Fracture load data were**

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analyzed using the Kruskal-Wallis test (α=0.05) for weakened roots, one-way analysis of variance, and Tukey test ($p<0.05$) for non-weakened roots, and Student *t*-test ($p<0.05$) compared nonweakened vs weakened roots for the same post system.

Results: **For the preliminary survival results, FP-W showed a higher survival rate when compared with CPC (gold/Ni). For the fracture load (N), the statistical analysis ($p<0.0001$) presented differences among the weakened groups: CPC-gold (541.4) = CPC-Ni (642.6) > FP (282.2) = FP-W (274.1) = FP-RC (216.6). No differences were observed for the groups that were nonweakened (majority of favorable failures): CPC-gold (459.3) = CPC-Ni (422.0) = FP (347.9). Weakened roots restored with CPC-gold promoted high values of load fracture and unfavorable failure rates.**

Conclusion: **Cast post and cores or fiber posts can be used for restoring nonweakened roots. However, for weakened roots, a fiber post with a wider cervical emerging diameter appears to be a better alternative when compared with cast post and cores.**

INTRODUCTION

Depending on the degree of destruction of coronary tooth structure, endodontically treated teeth often require anchorage to retain a restoration.[1] Thus, the two primary functions of intracanal posts are 1) to provide retention for a coronal restoration, which replaces the lost crown structure,[2,3] and 2) to transmit minimal stress to the tooth structure, so as to prevent root fracture.[4-6]

The ideal elastic modulus (E) for a retainer should be as similar as possible to that of dentin; however, different materials with different elastic moduli can be indicated as retainers (E dentin = 20 GPa, E noble metal alloy = 90 GPa, E titanium = 190 GPa, E glass fiber = 20-40 GPa, E composite = 5-25 GPa, E polyethylene fiber = 3.2 GPa).[1,7] Studies involving finite element analysis and photoelastic analysis showed that cast post and cores or prefabricated rigid posts (stainless steel, titanium, and zirconia) transfer higher stresses to the surrounding dentin when compared with fiber retainers.[6,8-10] Thus, it is believed that a rigid retainer can be associated with high rates of unfavorable failures in *in vitro*[11-13] and *in vivo* studies.[14]

The restoration of endodontically treated teeth becomes more complicated if the root is excessively weakened, because of the absence of the crown or loss of intraradicular dentin.[15,16] In these cases, teeth are unable to support high levels of forces during mastication[17-19] and have a higher risk of catastrophic fractures.[20]

Several materials have been associated with fiber posts to restore weakened roots, including fiber ribbons, accessory posts,[21] and composite resins.[22] Those materials have achieved favorable results for both bond strength and load fracture and usually present favorable failures in *in vitro* studies.[16,23-26]

The behavior of roots restored with retainers with different E may have different outcomes under cyclic loading; thus, mechanical cycling has been used to evaluate possible outcomes, taking into account different scenarios (roots or teeth restored with different materials and E).[27-29] Even with the limitations of *in vitro* studies, mechanical fatigue tests are carried out in a humid environment as a method that best approximates the clinical behavior of different materials and restorative techniques, reproducing, for example, the effects of restorative materials with different E on the whole tooth-restoration assembly. Fatigue is a type of test that may lead to fracture of a structure after repeated loads that can be explained due to microscopic crack propagation from areas of stress concentration, typically in regions of microscopic or molecular structural defects.[30-33]

Furthermore, survival analysis can be used to estimate survival and to interpret the function of an event; this function can also be used to compare different groups and to assess the relationship between explanatory variables and the frequency of the event of interest.[34] Some clinical studies have used this technique to evaluate therapies for restoring endodontically treated teeth, taking into account such variables as the type of canals, number of remaining walls, and types of retainers.[35-43]

In the case of *in vitro* studies, this analysis can be used to evaluate the probability of restored teeth surviving a period of evaluation under certain test conditions (eg, mechanical cycling parameters). Within this context, few studies have evaluated the *in vitro* survival rate of weakened roots restored with different intracanal retainers by the Kaplan-Meier method.

Thus, this *in vitro* study had the following objectives: 1) evaluate the fracture load of weakened and nonweakened roots restored with different intracanal retainers after mechanical cycling and 2) evaluate the main method of survival of the

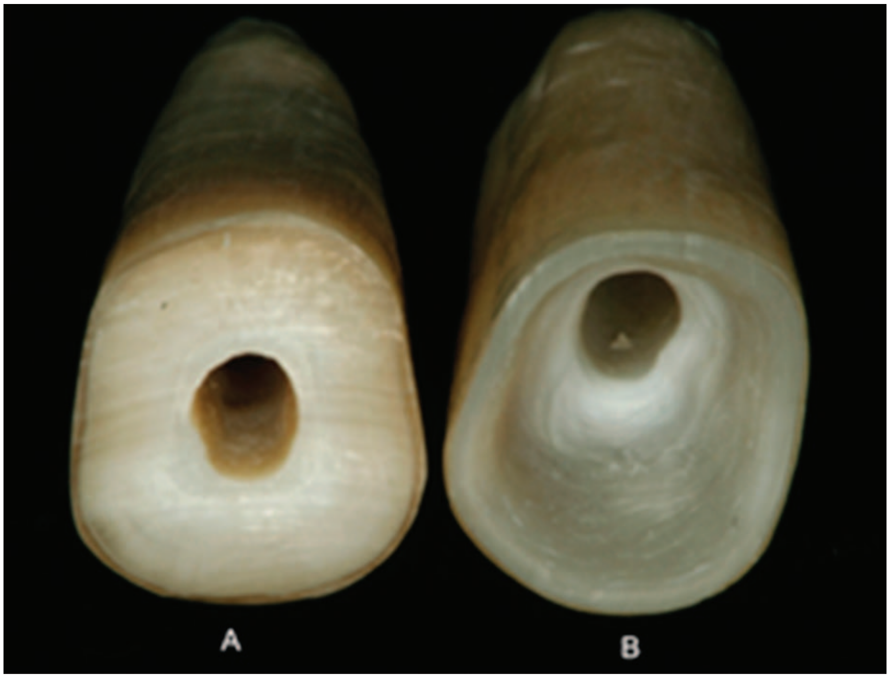

Figure 1. *Images of nonweakened roots (A) and weakened roots (B).*

specimens, using the Kaplan-Meier test, after 1.5 million cycles.

Thus, the scientific hypotheses were the following: 1) nonweakened roots restored with fiber cores would not present a difference in the fracture load values when compared with cast post and cores; (2) weakened roots restored with cast post and cores would present lower values of fracture load when compared with fiber posts; (3) nonweakened roots would present superior load when compared with weakened roots, independent of the restorative approach; and (4) nonweakened roots would present superior survival rates in relation to weakened roots.

METHODS AND MATERIALS

Selection and Preparation of Specimens

Bovine incisors were analyzed with a loupe (4× magnification, EyeMag Pro S, Carl Zeiss, Gottingen, Germany) to detect possible failures (fractures, fissures, or cracks) that might bias the results (exclusion criteria). After specimen selection (N=80), the coronal portions of each tooth were removed to standardize the length of the specimens at 16 mm. As another inclusion criteria, the mesiodistal and buccolingual dimensions of the cervical portion of the roots were measured with a caliper (Starrett 727, Starrett Indústria e Comercio Ltda, Itu, Brazil), and only teeth that exhibited values between 4 and 6 mm were included in the study to standardize the size of the roots.

Afterward, the specimens were divided into eight (n=10) groups according to the restorative approach and the presence or lack of canal weakening. Randomization was accomplished by numbering the specimens from 1 to 80, and eight random sequences of 10 numbers were generated by the computer program Random Allocator (developed by M. Saghaei, Department of Anesthesia, Isfahan University of Medical Sciences, Isfahan, Iran).

All specimens were initially prepared at a length of 10 mm with the No. 2 drill of the fiber post system White Post (White Post DC, FGM, Joinville, Brazil). In the weakened groups, the intracanal dentin was removed using a diamond-tapered drill (4137, KG Sorensen, Cotia, Brazil). Weakening was performed in the most coronal portion of the root up to 6 mm deep, standardizing the remaining dentin thickness at 0.5 mm (Figure 1B) to simulate the most hostile scenario of endodontically treated teeth.

To simulate the periodontal ligament, all roots from the apex to 3 mm apical from the coronal surface were coated with a 0.3-mm-thick layer of wax (Lysanda, São Paulo, Brazil) that was liquefied in a container at a standardized temperature of 70°C (to check the thickness of wax, we used a digital caliper to measure the distance mesiodistal and buccolingual before and after immersion of the root in the wax).

Subsequently, the drill of the post system was inserted into the canal and connected to a surveyor

(B2, BioArt, São Carlos, Brazil), keeping the whole tooth and drill parallel to the *y*-axis. Acrylic resin (VIPI Flash, VIPI, Pirassununga, Brazil) was placed in a PVC cylinder (h: 20 mm, Ø: 12 mm), and each root was embedded in resin up to 3 mm apical from the most coronal portion.

After polymerization of the resin, the roots were separated from the resin and the wax was removed. Then, an elastomeric material (Impregum F, 3M-Espe, Seefeld, Germany) was inserted into the "false socket," the root was repositioned in the PVC, and the excess elastomeric material was removed with a scalpel blade.[44]

Production and Cementation of Intracanal Posts

Gold and Ni-Cr Alloy Cast Post and Core (CPC-Gold/CPC-Ni)—Conventional procedures were performed for the cast post and core (CPC) production: patterns of the intracanal post space and core were made with acrylic resin (Duralay, Reliance Dental Mfg Co, Worth, IL) followed by casting, as recommended by the manufacturer (gold alloy, La Croix 2, La Croix Dental Alloys, Rio de Janeiro, Brazil; Ni-Cr alloy, Wironia Light, Bego, Bremen, Germany). The cores had their dimensions standardized by using identical plastic matrices.[45,46]

The CPCs were evaluated for adaptability and cemented as follows: 1) posts were cleaned with isopropyl alcohol and the post root portion was air-abraded with aluminum oxide particles (110 μm, pressure: 2.8 bars, 10 mm distance, and 15 seconds); 2) root dentin was conditioned with 37% phosphoric acid (Condac 37, FGM) for 15 seconds, washed with water for 15 seconds, and the excess water was removed with No. 80 paper points (Dentsply, Petrópolis, Brazil); 3) a photo-cured adhesive agent (Ambar, FGM) was applied with a microbrush, and the excess was removed with paper cones and photo activated for 20 seconds with a high-power LED (1200 mW/cm^2, RadiiCal, SDI, Australia); and 4) equal amounts of the dual-cured resin cement pastes (AllCem, FGM) were mixed and inserted into the canals using a No. 40 Lentulo spiral (Dentsply Maillefer, Catanduva, Brazil), followed by insertion of the post into the root canal, excess cement was removed with a microbrush, and the remaining resin was photo activated for 10 seconds in the incisal surface and another 10 seconds at each face. The specimens were stored in distilled water at 37°C for 24 hours prior to the metal crown production.

Conventional Prefabricated Fiber Posts (FP)—The No. 2 fiber posts (White Post DC No. 2) were positioned in the canal, and the coronal part was cut, preserving a 5-mm height from the coronal portion. The fiber posts were cleaned with isopropyl alcohol, and the surface received an MPS-based silane coupling agent (Prosil, FGM). Cementation was carried out as mentioned previously.

Afterward, the core construction was performed with a composite resin (Oppalis, FGM). First, a layer of resin was applied on the post and coronal dentin and photo activated for 30 seconds. Then, resin was inserted inside standard plastic templates (as used for CPCs), which was positioned on the post and dentin, followed by photo activation (20 seconds) on each face, and the matrices were removed. The specimens were stored in distilled water (37°C) for 24 hours prior to the metal crown production.

Wider Prefabricated Fiber Posts (FP-W)—The dowels used for this group were the No. 2 Double Cone Special (White Post DC No. 2E). The preparation of the specimens was similar to the FP groups. These posts are considered "special" because of their wider cervical diameter, which is recommended for roots with enlarged root canals. The post cementation was carried out as previously mentioned.

Fiber Posts Relined With Composite Resin (FP-CR)—Fiber posts (White Post DC No. 2) were used for this group.

The following procedures were performed: 1) the fiber posts were cleaned with isopropyl alcohol and silanized as mentioned previously; 2) the walls of the intracanal dentin were isolated by applying hydro-soluble insulation (K-Y gel, Johnson & Johnson, São José dos Campos, Brazil) to avoid composite resin bonding; 3) the composite resin was condensed inside the canal, the post was positioned, and the resin was light cured for 20 seconds from the occlusal surface; 4) the assembly was removed from the canal, photo activated for 40 seconds, and reinserted to verify adaptation; 5) the post/composite resin assembly was conditioned with 37% phosphoric acid for 60 seconds, washed with distilled water for 15 seconds, and dried with absorbent paper; 6) a thin layer of adhesive was applied and photo activated for 40 seconds; and 7) the adhesive was applied on the intraradicular dentin, and the cementation procedures were performed as mentioned previously for other groups restored with fiber posts.

Preparation and Cementation of Metal Crowns

Eighty metal crowns were fabricated according to the anatomy of a maxillary canine, as follows: 1) each prosthetic preparation was molded with a vinylpolysiloxane material (addition silicone, Elite Double 8, Zhermack, Rovigo, Italy), and a master die was fabricated (Durone, Dentsply); 2) each crown was waxed on the die (Newwax, Technew, Campo Grande, Brazil) using standardized maxillary canine plastic templates; and 3) casting was accomplished using the lost-wax technique as recommended by the manufacturer (nonnoble alloy, Wironia Light).

The crowns were examined for adaptation, and the inner surfaces were air-abraded with aluminum oxide (110 μm; Blue Equipment, São José do Rio Preto, Brazil) and adhesively cemented, using the same adhesive system and resin cement described previously. A load of 5 kg was applied on the crown by means of a static press during cementation, and the excess cement was removed.

Mechanical Cycling

For mechanical cycling, the specimens were subjected to the following protocol: 45° angle to the long axis of the root, water immersion (±37°C), pulse load of 0 N to 130 N, frequency of 2.2 Hz, and 1,500,000 pulses on the crown at a point located 2 mm below the incisal edge on the lingual aspect of the specimen.

According to Wiskott and others,[47] 1 million cycles are equivalent to one year of clinical service; therefore, the present study simulated approximately 1.5 years of clinical service.

For the survival analysis, the roots were evaluated for the presence of cracks. After each set of 50,000 cycles, all roots were evaluated by a calibrated operator. The specimens were monitored to check the time and the approximate size of the failure (if it occurred). The evaluation of the failure was performed with a loupe (4× magnification, EyeMag Pro S, Carl Zeiss). The final mode of failure was observed with a stereomicroscope (Discovery V20, Carl Zeiss). The specimens that survived mechanical cycling were submitted to a monotonic fracture load and subsequent failure analysis.

Fracture Load Test

Each specimen was positioned on a device that was aligned at an angle of 45° to the long axis of the tooth. A universal testing machine (DL-1000, Emic, Sao Jose dos Pinhais, Brazil) was used to apply a constant load at a crosshead speed of 1 mm/min until failure. The threshold of failure was defined as the point at which the force (N) reached a maximum value at root fracture, bending of the post, or detachment of the core-post assembly.

Failure Analysis

The failures that occurred during the tests were classified as favorable (above the 3 mm corresponding to the simulated bone level) and unfavorable (below the simulated bone level). For failure analysis, the roots were stained with pens (blue marker, Faber-Castell, São Carlos, Brazil), and the ink was partially removed using a cotton ball and 70% alcohol to visualize the fractures. The procedure was performed before and after the fracture load test.

Data Analysis

Considering that every final failure comes from an initial failure, events such as root fracture were measured as a "crack" event. Events of marginal misfit, when not associated with root cracks, were not considered an outcome.

Survival rates were estimated with the Kaplan-Meier technique, using STATA 12.0 (Stata Corporation, College Station, TX, USA). The differences between the survival rates according to the study groups were analyzed using the log-rank test ($p \leq 0.05$).

For fracture load data, the Shapiro-Wilk test did not show a normal distribution for the weakened roots' data; consequently, a nonparametric test (Kruskal-Wallis, $\alpha = 0.05$) was used to analyze it. In contrast, data from other conditions had normal distribution: nonweakened roots were compared among themselves (one-way analysis of variance ANOVA and Tukey tests, $p < 0.05$).

The Student *t*-test ($p < 0.05$) compared nonweakened vs weakened roots for the same post system.

RESULTS

Mechanical Cycling: Descriptive Analysis and Survival Preliminary Results (Kaplan-Meier Method)

Among the weakened roots, five specimens fractured after 1.5 million cycles: two failures occurred in the FP group (50,000 and 100,000 cycles, unfavorable and favorable failures, respectively), one failure in the CPC-gold group (700,000 cycles, unfavorable), and two failures in the FP-CR group (150,000 and 1,150,000 cycles, favorable and unfavorable failures, respectively). For the nonweakened groups, two specimens fractured in the FP group (50,000 and 110,000 cycles, both favorable failures). The mechanical failures during cycling are presented in Table 1.

Table 1: *Qualitative assessment of the failures after fracture load and during mechanical cycling for the outcome fracture*

			STUDY GROUPS								
			Non-weakened			weakened					
			CPC-gold (n=10)	CPC-Ni (n=10)	FP (n=8)	CPC-gold (n=9)	CPC-Ni (n=10)	FP (n=8)	FP-W (n=10)	FP-CR (n=8)	TOTAL
FAILURES AFTER FRACTURE LOAD	Pattern of Failure	Favorable	4	7	6	0	0	0	1	1	19
		Unfavorable	6	3	2	9	10	8	9	7	54
	Failure place	Mesial crack	7	7	7	10	9	9	7	6	62
		Buccal crack	3	1	4	4	2	4	4	3	25
		Distal crack	5	5	11	8	8	6	9	6	58
		Lingual crack	1	0	1	2	1	0	0	0	5
		Fracture post	0	1	0	0	0	0	0	0	1
	Failure mode	Mesiodistal	5	6	9	8	7	5	6	4	50
		buccolingual	0	0	0	0	0	0	0	0	0
FAILURES DURING MECHANICAL CYCLING	Amount and pattern of failure	Favorable (F)	-	-	2 failures (1 & 2)	-	-	1 failure (4)	-	1 failure (6)	4
		Unfavorable (U)	-	-	-	1failure (3)	-	1 failure (5)	-	1 failure (7)	3
					failure 1 / failure 2	failure 3		failure 4 / failure 5		failure 6 / failure 7	
	Failure place	Mesial crack	-	-	x / x	x	-	x / x	-	x / x	7
		Vestibular crack	-	-	- / -	-	-	- / -	-	- / -	-
		Distal crack	-	-	x / x	x	-	x / x	-	x / x	7
		Lingual crack	-	-	- / -	-	-	- / -	-	- / -	-
		Fracture post	-	-	- / -	-	-	- /	-	- / x	1
	Failure mode	Mesiodistal	-	-	x / x	x	-	x / x	-	x / x	7
		buccolingual	-	-	- / -	-	-	- / -	-	- / -	-

CPC-gold, cast post and core made of gold alloy; CPC-Ni, cast post and core made of Ni-Cr alloy; FP, glass fiber posts; FP-W, glass fiber posts with a wider coronal diameter; FP-CR, fiber posts relined with composite resin.

For the survival analysis, three approaches were performed (Table 2).

1) Comparison between groups according to root condition, weakened vs nonweakened (Figure 2A)—KM analysis showed no difference between the two conditions (log-rank test, p=0.09). However, the survival rate was 0.43 (SEM = 0.09) for nonweakened roots and 0.23 (SEM = 0.07) for weakened roots; thus, the probability that weakened roots exceed 1.5 million cycles without showing cracks (event/primary outcome) was 23%, while the probability for the nonweakened roots was 43%. The median survival for weakened roots was 350,000 cycles (EP = 205,396). For the nonweakened roots, the median was 1,150,000 cycles (EP = 273,252).

Table 2: *Mean (±standard error) of the data survival rates and Log-rank test*[a]

	Weakened roots canals	
	Yes	No
Restoring strategies	Mean (SE)	Mean (SE)
CPC-Gold	750000 (200499.4) [a, B]	1070000 (123733.6) [a, A]
CPC-Ni	710000 (190368.1) [a, B]	1030000 (190814) [a, A]
FP	670000 (215893.5) [a, AB]	710000 (209141.1) [a, A]
FP-W	1085000 (201128.1) [A]	-
FP-CR	955000 (198172.9) [AB]	-

Different lowercase letters indicate differences between the types of weakened; Different capital letters indicate differences between restoration strategies.

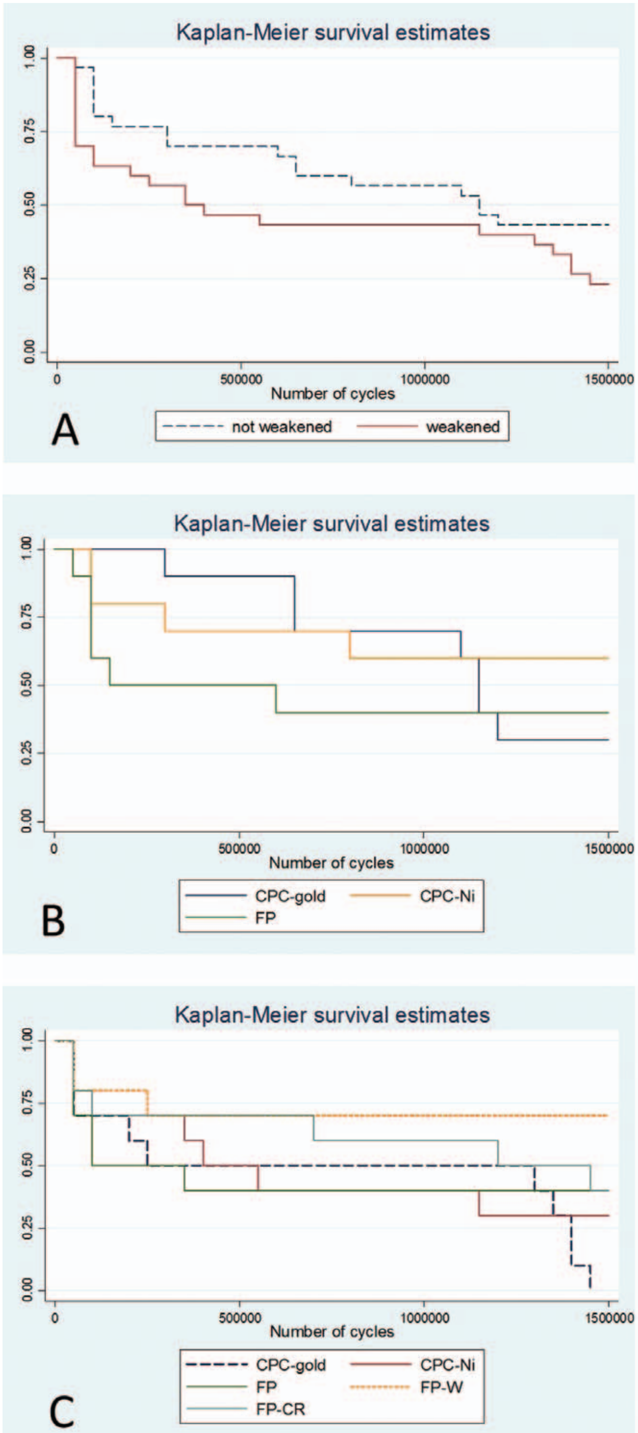

Figure 2. *Survival curves estimated by using the Kaplan-Meier method for the occurrence of cracks according to condition of root (A), according to type of strategy (nonweakened condition of the root) (B), and according to strategy type (weakened roots) (C).*

2) Comparison of restoring strategies for nonweakened roots (Figure 2B)—It is noted that the survival curves of the strategies were similar (log-rank test, p=0.54, CPC-gold = CPC-Ni = FP) and that they had similar survival rates estimated during the observation time.

3) Comparison of restoring strategies for weakened roots (Figure 2C)—It is noted that the only probabilities of survival of the specimens of the FP-W group had higher survival rates when compared with the specimens of both of the CPC groups (log-rank test, p=0.004).

Fracture Load

Table 3 presents the average values and standard deviation as well as statistical inferences.

For the groups with nonweakened roots, the one-way ANOVA showed that the restoring strategy was not significant (p=0.558; study groups were statistically similar).

For the groups with weakened roots, the Kruskal-Wallis test showed that the restorative strategy was significant (p=0.000; CPC-gold = CPC-Ni > FP > FP-W > FP-CR).

The Student t-tests (Table 3) indicated that weakened and nonweakened specimens did not differ statistically for each restoring strategy.

Failure Analysis

The failures during mechanical cycling are shown in Table 1 and Figure 3A-F.

After the fracture load test, the nonweakened specimens had 39% unfavorable fractures (Table 1; Figure 4A,D), whereas the weakened specimens had 95% unfavorable fractures (Table 1; Figure 4B,C).

The location of failures was evaluated during mechanical cycling and after the fracture load tests. It is noted that the vast majority of failures were cracks in the mesial and distal surfaces of roots in different radicular thirds.

DISCUSSION

The first research hypothesis of this current study was accepted, since no differences were noted between the three restoring strategies (CPC-gold, CPC-Ni, FP) when the roots were not weakened. These results are in agreement with those of Maccari and others,[12] Mitsui and others,[3] and Ni and others,[48] all of whom also observed no differences between metal, ceramic, and fiber posts. However, those studies contrast with those of Özcan and

Table 3: *Mean (±standard deviation) of the Data Fracture Load (N) and Tukey's Test*

Restoring strategies	Weakened roots canals: Yes Mean (SD)	Weakened roots canals: No Mean (SD)	P value*
CPC-Gold	541.4 (227.4) a, A	459.3 (111.1) a, A	p = 0.135
CPC-Ni	642.6 (219.5) a, A	422.0 (151.9) a, A	p = 0.221
FP	282.2 (64.7) a, B	347.9 (91.8) a, A	p = 0.120
FP-W	274.1 (51.3) B	-	-
FP-CR	216.6 (63.6) B	-	-

*Different lowercase letters indicate differences between the types of weakened (Kruskal-Wallis; a=0.05); Different capital letters indicate differences between restoration strategies; * P-value from Student t test, comparing weakened vs non-weakening for each restoring strategy.*

Valandro[49] and Kaur and others,[13] since cast post and cores and titanium posts had higher values of fracture load when compared with fiber posts in the latter studies.

The disagreement between the results of this current study with the findings of Özcan and Valandro[49] may be that the latter study did not use crowns to cover the cores. Without the protection of the crown, the core becomes more susceptible to failure and the load is transmitted directly to the post/core assembly.[50] According to Kaur and others,[13] the disagreement between the current results may be attributed to the greater removal of dentin conducted by the researchers in that study during preparation of specimens restored with cast post and cores, contrasting with the more conservative preparation performed in the present study. While the specimens in the study by Kaur and others had enlarged canals,[13] the current study used only the drill of the post system in the preparation of roots restored with cast post and cores.

Finite element analysis studies have shown that greater volumes of retainers present greater stress concentration in the dental structure.[4,6] The greater volume of the retainer and higher stress concentration may have been responsible for generating a

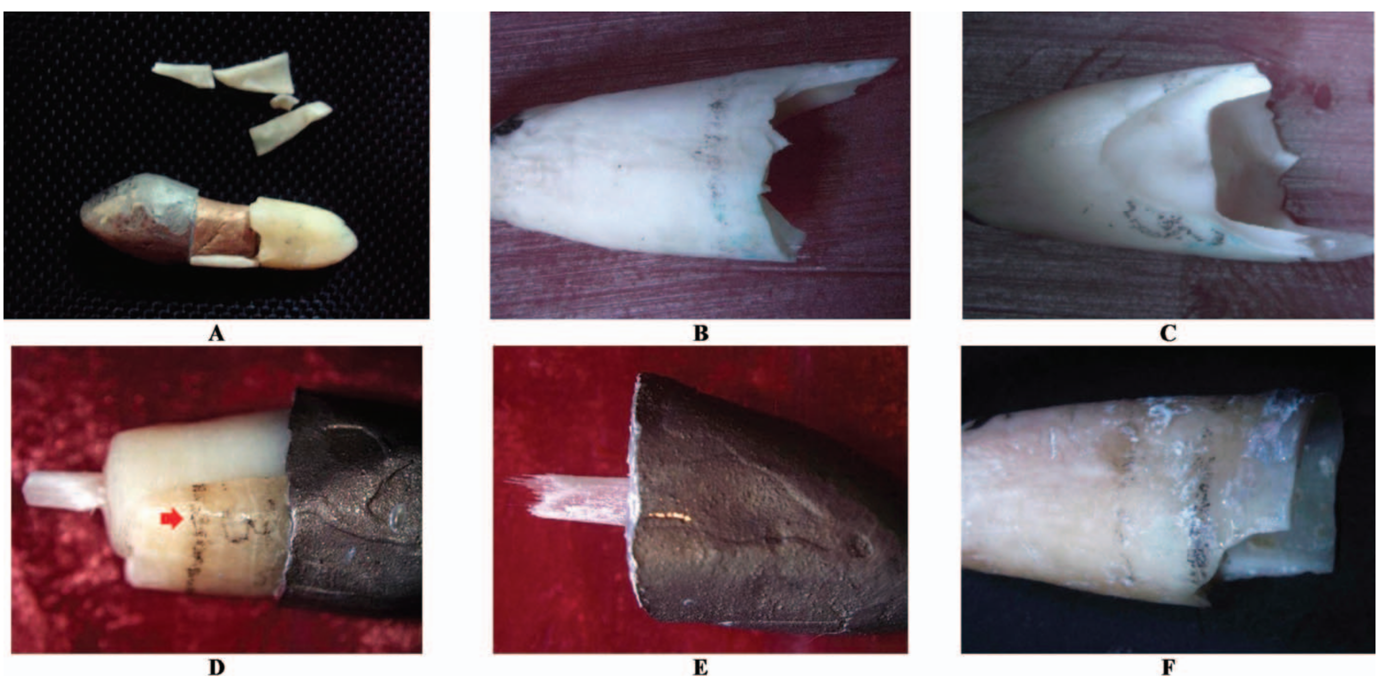

Figure 3. *Representative images of failures occurring during mechanical cycling. (A) Unfavorable fracture in CPC-gold weakened group (failure 3 as typed by Table 1). (B) Unfavorable fracture in FP weakened group (failure 5 as typed by Table 1). (C) FP weakened from the labial view (failure 5 as typed by Table 1). (D) FP-CR: unfavorable fracture (arrow indicates the bone limit simulated; failure 7 as typed by Table 1). (E) FP-CR: fracture of post/core (failure 6 as typed by Table 1). (F) Fracture favorable in FP weakened group (failure 1 as typed by Table 1).*

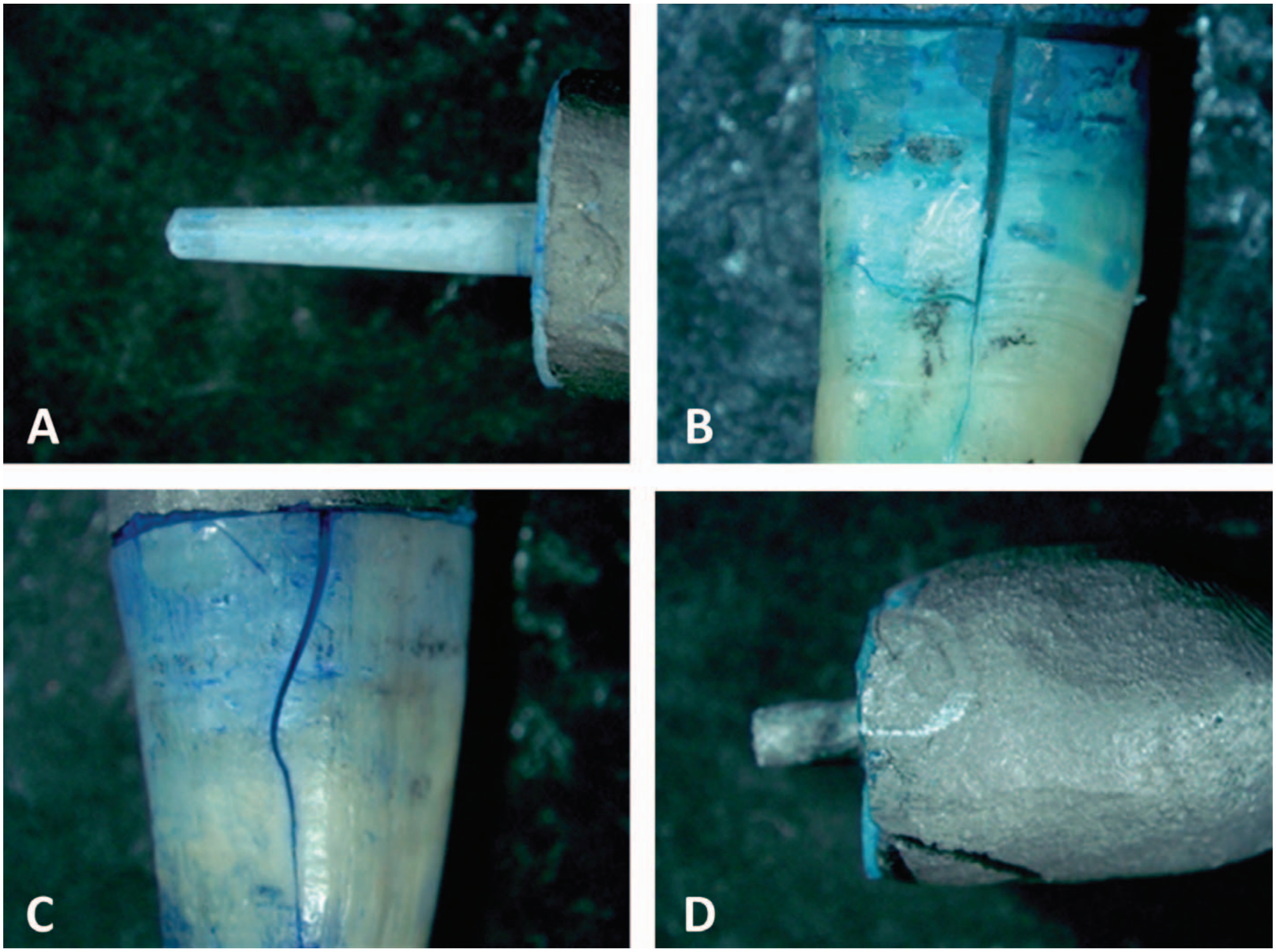

Figure 4. *Representative images of failures occurred after the fracture load test. (A) FP nonweakened: displacement post/core/crown. (B) CPC-gold weakened: crack on the mesial surface. (C) FP weakened: crack on the distal surface. (D) CPC-Ni nonweakened: fracture of the cast and post core.*

wedge effect and the unfavorable failures for Kaur and others,[13] something also observed by other studies,[6,50,51] a result that was not found in the present study, in which the tooth structure was preserved and a predominance of favorable failures was achieved.[2,12,52-55]

When considering the weakened roots, the cast post and core groups had higher mean values of fracture load when compared with the groups restored with fiber posts (Table 3); therefore, the second hypothesis was rejected.

The current results partially agree with those of Silva and others,[22] since the fracture load values of fiber posts were similar; however, there is disagreement in relation to the roots restored with cast post and cores. While Silva and others[22] had lower values of load to fracture for the specimens restored with cast post and cores, the present study demonstrated higher values for the same condition, which may be associated with the greater depth of weakening in the Silva and others study,[22] which maintained the thickness of remaining dentin of 1 mm up to an intracanal depth of 9 mm. Studies regarding widely weakened roots[20,21,23,26,56] restored with cast post and cores presented results similar to that study, considering fracture load and the predominance of unfavorable failures. Cast post and cores had higher fracture load values and more unfavorable failures than the groups restored with fiber posts and fiber posts associated with materials that had an E similar to that of dentin (composite resin, accessory posts, and fiber ribbons).

When roots are restored with fiber posts or fiber posts associated with materials with properties compatible to dentin, a more homogeneous stress distribution is observed on the dental structure when compared with cast post and cores.[4,6,57,58] Even though the tensions on roots restored with fiber posts are concentrated in the cervical third,[8,59,61] weakening was performed in this present study up to an intraradicular depth of 6 mm, which could have increased the number of unfavorable failures.

When evaluating the failures in weakened roots, 95% of the failures were unfavorable (45 from 47). Favorable failures occurred in the groups restored with fiber posts (FP-CR and FP-W). Bonfante and others[21] had more unfavorable failures for fiber posts and cast post and cores. Such divergence of results could be associated with the difference in weakening performed in these studies. While 0.5 mm of the dentin walls was maintained in the present study, Bonfante and others[21] maintained a thickness between 1.25 and 1.5 mm in the mesiodistal direction and 2.25 and 2.5 mm in the buccolingual direction (ie, more dentinal structure to support the applied loads).

When comparing weakened and nonweakened roots with the same retainer (Table 3), the *t*-test ($p<0.05$) did not show a difference between the weakened and nonweakened groups. Hence, the third hypothesis was rejected.

The current results are in agreement with Silva and others[22] regarding weakened and nonweakened roots restored with fiber posts. However, the current results presented divergences regarding the CPC-Ni strategy, since Silva and others[22] noted higher mean values of fracture load for nonweakened roots restored with cast posts than for weakened roots.

While the Student *t*-test showed no difference between the groups in terms of fracture load, the failure analysis showed a predominance of unfavorable failures in the weakened roots when compared with nonweakened roots, a result also observed in many studies.[12,21,22] This result can be explained by the preservation of dental structure.[50,53,55,56]

The fourth hypothesis was rejected, since the survival analysis showed no differences between the weakened and nonweakened roots (Figure 2A). On the other hand, the restorative strategies for the nonweakened condition (Figure 2B) were similar. For the weakened roots (Figure 2C), the estimated survival was higher for the FP-W strategy when compared with the CPC (gold and Ni) strategies. The discussion of the results was based on studies regarding fracture load and finite element analysis, since the authors were unaware of the existence of a study to assess the estimated survival rate of weakened and nonweakened roots restored with intraradicular retainers.

Studies have stated that weakened teeth restored with root posts with an E similar to that of dentin have a more homogeneous stress distribution on the dental structure, promoting favorable failures when compared with more rigid posts.[4,6,8,58,59] In this context, Maccari and others,[12] Kivanç and others,[19] Bonfante and others,[21] Silva and others,[22] and Akkayan and Gülmez[62] demonstrated a high percentage of catastrophic root failures when using rigid posts (metallic and ceramic) when compared with prefabricated fiber posts after fracture load tests, supporting the findings found in the current study for FP-W vs CPC strategies.

Regarding the failure pattern obtained in the weakened and nonweakened roots, it is feasible to notice that, according to Table 1, fractures were mainly on the mesial and distal surfaces. To assess the effects of a load applied at an angle of 45°, it is essential to understand that this force can be decomposed into two components by means of the Parallelogram Law.[63] Decomposing the force into a vector in a Cartesian axis (Figure 5), one obtains the Cartesian components Fx and Fy (Figure 6A).

Concerning the effects of the components Fx and Fy on the specimens tested, the axial force component Fx produces compressive loading, generating stress uniformly distributed in the cross section (Figure 6B). Component Fy carries transverse force leading to bending of the structure, producing normal stresses of tensile and compression (Figure

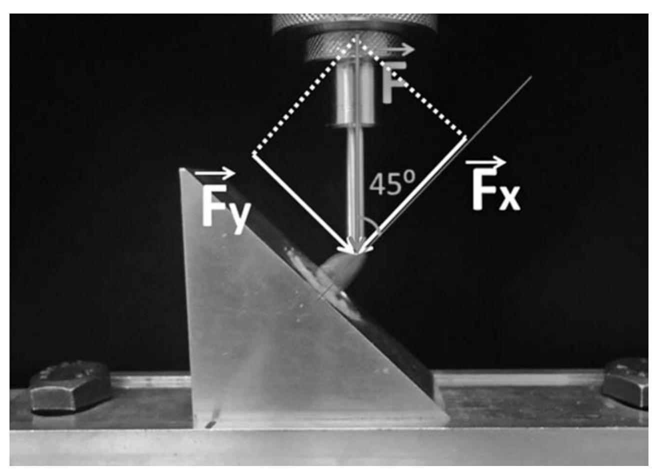

Figure 5. *Diagram of the vectors decomposition on the Cartesian coordinate system of the original force F (45°) on the specimen.*

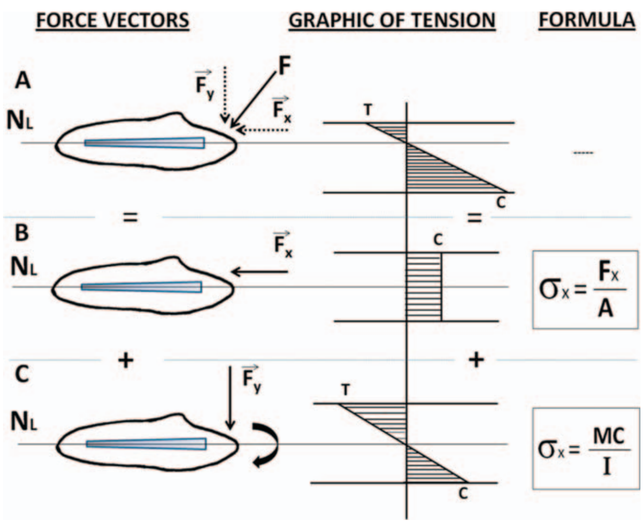

Figure 6. *Diagram of the normal stresses (A), compression normal stress (B), and bending stress (C). Force vectors acting on the tooth structure expressed by tension graphs and their formulas. F, original force 45°; Fx, horizontal component of F; Fy, vertical component of F; NL, neutral line; T, tensile; C, compression; σ_X, normal stress in Fx; A, sectional area; M, bending moment; C of the formula, distance of the neutral line to the fiber experiencing most F in the specimen; I, moment of inertia of area. Inside the tooth, the retainer is defined with a blue post.*

6C). The force Fy induced shear stress in parallel planes to the longitudinal axis of the structure due to the transverse loading (Figure 7).

In the case of a dental element restored with intracanal posts, while Fx causes only compressive stresses uniformly distributed in the transverse plane (Figure 6B), Fy causes tensile stresses on the lingual surface and compression on the buccal surface (Figure 6C) and zero stress in the center of the dental element. In this area, there is the maximum shear stress caused by the component Fy (Figure 7).[63] Since the post is placed in the root canal, in the central area of the tooth, it is subject to minimum tensile and minimum compressive stress and maximum shear stress. This shear zone can be shifted to the region where the volume of the structure is larger.[64] In the case study, bovine roots with a trapezoidal geometric shape with the larger base facing to the buccal surface (Figure 1B) have been used. Therefore, the shear zone would be moved to the buccal area.

Given this information, it is feasible to believe that a sequence of events can lead to the ultimate prevalent failure in most failures (mesial-distal fracture mode with full coronal displacement; Table 1; Figure 3A-D,F; Figure 4B,C). Because of the shear stress, it may occur primarily at the interface of adhesive failure (post/dentin), which leads to decementation of the restored assembly (post-crown). Thus, the retainer would be loose in the canal, being no longer a unique structure. The consequence of this is that the buccal wall of the roots suffer higher stress (compression) compared with the lingual wall.

The combination of all of the factors mentioned above may have led to a mesiodistal fracture mode closer to the buccal face (Figure 8A-E). However, it is important to note that more studies should be conducted to confirm the failure hypothesis. The strain gauge method can be a useful methodology, although caution must be taken in interpreting *in vitro* studies evaluating the restoration of endodontically treated teeth.

This present study has some limitations. Loading of materials by mechanical cycling is the *in vitro* mechanical procedure that is closest to the real conditions of aging, although it is still not possible to accurately reproduce the *in vivo* environment. Mechanical cycling has fixed execution protocols, such as value and load direction, humidity, and temperature, which limit the simulation of the *in vivo* real conditions. Thus, through a load considered of intermediate value by the authors, the specimens were aged to verify the behavior of the restorations within the period of evaluation, something that might not be possible using a lower load of cycling.

The fracture load test has limitations as well: load application until failure of the structure, high values of loading (not correspondent to *in vivo*), and high standard deviations are present in studies that use this methodology.

Further longitudinal studies evaluating survival and/or randomized controlled trials should be performed to define clinical predictability and plausibility of restoring therapies for weakened roots.

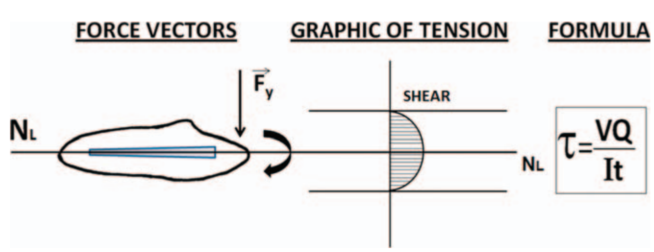

Figure 7. *Diagram of the shear stress acting on the tooth structure expressed by the graph of tension and its formula. τ, shear stress; V, load (in this case represented by the value of Fy); Q, static moment of area; I, moment of inertia of the area; t, thickness of the flat section area.*

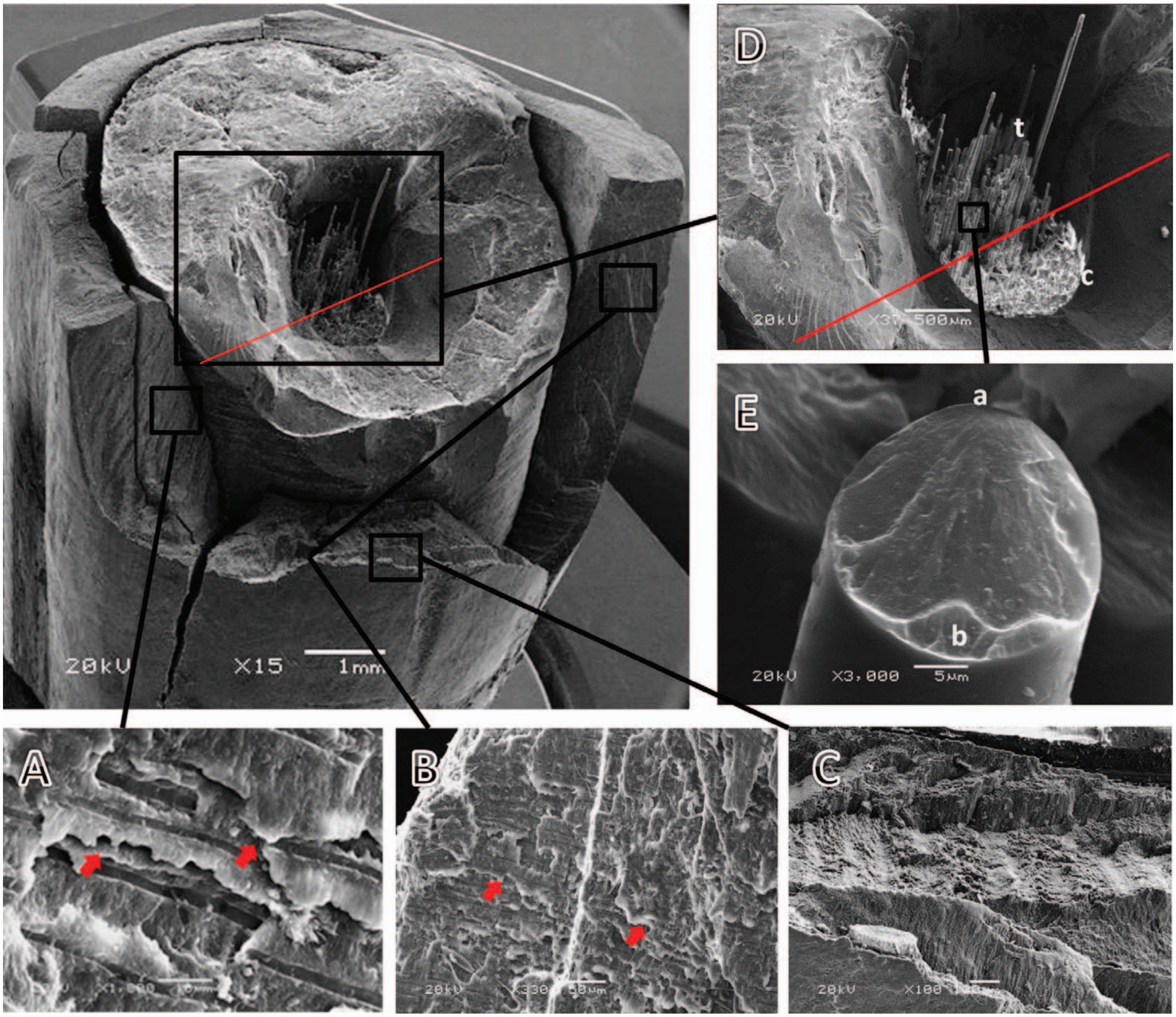

Figure 8. *Representative micrographs of a specimen from group 8 (FP-CR) fractured during mechanical cycling. We can see the debonding of the restoring complex and fracture, which occurred in the buccal region, as explained by biomechanical principles cited previously. The red line refers to the neutral line of bending. (A,B). Micrograph of the fractures at the mesial and distal regions, respectively. It notes the red arrows through the peculiar characteristics related to this nature of fracture. The difference in plane for the "tear" structure and the presence of dentinal tubules. (C) Micrograph of buccal dentin wall. It appears to be a characteristic situation of "kneading" (typical "compression curl") of the buccal structure after breaking of the opposed lingual portion occurred by tensile stress. (D) Micrographs of the region of the fiber post. The red line refers to the neutral line in the post. It notes the difference between the areas of tensile (lingual "t") and compression (buccal "c") of the post. (E) Micrograph of a fiber situated in the tensile zone (lingual) of the post. By surface analysis, the fracture orientation appears to have occurred from "a" to "b." The "b" point represents the typical "compression curl" (tell-tale feature), which appears in the bend structure.*

CONCLUSION

- The tested restoring strategies were similar when restoring nonweakened roots. Thus, roots with an adequate amount of remaining dental structure can be restored using any evaluated intracanal post system.
- Taking into account the survival rate findings for the weakened roots, the fiber post with a wider cervical emerging diameter appears to be the best restorative alternative.
- The cast post and cores (gold and Ni) promoted higher values of fracture load of weakened roots and higher levels of unfavorable fractures.
- Weakened roots are highly susceptible to cracks and catastrophic failures in relation to nonweakened roots.

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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REFERENCES

1. Baldissara P (2003) Mechanical properties and *in vitro* studies In: Ferrari M, Scotti R (eds) *Fiber Posts: Theoretical Considerations and clinical Applications* Masson, Milan, Italy 39-51.
2. Trope M, Maltz DO, & Tronstad L (1985) Resistance to fracture of restored endodontically treated teeth *Endodontics & Dental Traumatology* **1(3)** 108-111.
3. Mitsui FH, Marchi GM, Pimenta LA, & Ferraresi PM (2004) In vitro study of fracture resistance of bovine roots using different intraradicular post systems *Quintessence International* **35(8)** 612-626.
4. de Castro-Albuquerque R, Polletto LT, Fontana RH, & Cimini CA (2003) Stress analysis of an upper central incisor restored with different posts *Journal of Oral Rehabilitation* **30(9)** 936-943.
5. Lanza A, Aversa R, Rengo S, Apicella D, & Apicella A (2005) 3D FEA of cemented steel, glass and carbon posts in a maxillary incisor *Dental Materials* **21(8)** 709-715.
6. Coelho CS, Biffi JC, Silva GR, Abrahão A, Campos RE, & Soares CJ (2009) Finite element analysis of weakened roots restored with composite resin and posts *Dental Materials Journal* **28(6)** 671-678.
7. Ferracane JL (2005) *Materials in Dentistry: Principles and Applications* Lippincott Williams & Wilkins, Philadelphia, Pa.
8. Meira JB, Espósito CO, Quitero MF, Poiate IA, Pfeifer CS, Tanaka CB, & Ballester RY (2009) Elastic modulus of posts and the risk of root fracture *Dental Traumatology* **25(4)** 394-398.
9. Yamamoto M, Miura H, Okada D, Komada W, & Masuoka D (2009) Photoelastic stress analysis of different post and core restoration methods *Dental Materials Journal* **28(2)** 204-211.
10. Asvanund P, & Morgano SM (2011) Photoelastic stress analysis of different prefabricated post-and-core materials *Dental Materials Journal* **30(5)** 684-690.
11. Mannocci F, Ferrari M, & Watson TF (1999) Intermittent loading of teeth restored using quartz fiber, carbon-quartz fiber, and zirconium dioxide ceramic root canal posts *Journal of Adhesive Dentistry* **1(2)** 153-158.
12. Maccari PCA, Conceição EN, & Nunes MF (2003) Fracture resistance of endodontically treated teeth restored with three different prefabricated esthetic posts *Journal of Esthetic and Restorative Dentistry* **15(1)** 25-30.
13. Kaur J, Verma PR, & Nagpal A (2011) Fracture resistance of endodontically treated teeth restored with different post systems a comparative study *Indian Journal of Dental Sciences* **3(3)** 5-9.
14. Ferrari M, Vichi A, & García-Godoy F (2000) Clinical evaluation of fiber-reinforced epoxy resin posts and cast post and cores *American Journal of Dentistry* **13(Spec No)** 15B-18B.
15. Erkut S, Eminkahyagil N, Imirzalioglu P, & Tunga U (2004) A technique for restoring an overflared root canal in an anterior tooth *Journal of Prosthetic Dentistry* **92(6)** 581-583.
16. Yoldas O, Akova T, & Uysal H (2005) An experimental analysis of stresses in simulated flared root canals subjected to various post-core applications *Journal of Oral Rehabilitation* **32(6)** 427-432.
17. Naumann M, Preuss A, & Frankenberger R (2006) Load capability of excessively flared teeth restored with fiber-reinforced composite posts and all-ceramic crowns *Operative Dentistry* **31(6)** 699-704.
18. Zogheib LV, Pereira JR, do Valle AL, de Oliveira JA, & Pegoraro LF (2008) Fracture resistance of weakened roots restored with composite resin and glass fiber post *Brazilian Dental Journal* **19(4)** 329-333.
19. Kivanç BH, Alaçam T, Ulusoy OI, Genç O, & Görgül G (2009) Fracture resistance of thin-walled roots restored with different post systems *International Endodontic Journal* **42(11)** 997-1003.
20. Fukui Y, Komada W, Yoshida K, Otake S, Okada D, & Miura H (2009) Effect of reinforcement with resin composite on fracture strength of structurally compromised roots *Dental Materials Journal* **28(5)** 602-609.
21. Bonfante G, Kaizer OB, Pegoraro LF, & do Valle AL (2007) Fracture strength of teeth with flared root canals restored with glass fibre posts *International Dental Journal* **57(3)** 153-160.
22. Silva GR, Santos-Filho PC, Simamoto-Júnior PC, Martins LR, Mota AS, & Soares CJ (2011) Effect of post type and restorative techniques on the strain and fracture resistance of flared incisor roots *Brazilian Dental Journal* **22(3)** 230-237.
23. Clavijo VGR, Reis JMSN, Kabbach W, Silva ALF, Oliveira OB Jr, & Andrade MF (2009) Fracture strength of flared bovine roots restored with different intraradicular posts *Journal of Applied Oral Science* **17(6)** 574-578.
24. Faria-e-Silva AL, Pedrosa-Filho CdeF, Menezes MdeS, Silveira DM, & Martins LR (2009) Effect of relining on fiber post retention to root canal *Journal of Applied Oral Science* **17(6)** 600-604.
25. Macedo VC, Faria-e-Silva AL, & Martins LR (2010) Effect of cement type, relining procedure, and length of cementation on pull-out bond strength of fiber posts *Journal of Endodontics* **36(9)** 1543-1546.
26. Aggarwal V, Singla M, Miglani S, & Kholi S (2012) Comparative evaluation of fracture resistance of structurally compromised canals restored with different dowel methods *Journal of Prosthodontics* **21(4)** 312-316.
27. Rosentritt M, Fürer C, Behr M, Lang R, & Handel G (2000) Comparison of *in vitro* fracture strength of metallic and tooth-coloured posts and cores *Journal of Oral Rehabilitation* **27(7)** 595-601.

28. Heydecke G, Butz F, Hussein A, & Strub JR (2002) Fracture strength after dynamic loading of endodontically treated teeth restored with different post-and-core systems *Journal of Prosthetic Dentistry* **87(4)** 438-445.

29. Dietschi D, Ardu S, Rossier-Gerber A, & Krejci I (2006) Adaptation of adhesive post and cores to dentin after *in vitro* occlusal loading: evaluation of post material influence *Journal of Adhesive Dentistry* **8(6)** 409-419.

30. Baldissara P, Zicari F, Valandro LF, & Scotti R (2006) Effect of root canal treatments on quartz fiber posts bonding root dentin *Journal of Endodontics* **32(10)** 985-988.

31. Bottino MA, Baldissara P, Valandro LF, Galhano GAP, & Scotti R (2007) Effects of mechanical cycling on the bonding of zirconia and fiber posts to human root dentin *Journal of Adhesive Dentistry* **9(3)** 327-331.

32. Scotti R, Valandro LF, Galhano, GA, Baldissara P, & Bottino MA (2006) Effect of post length on the fatigue resistance of bovine teeth restored with bonded fiber posts: a pilot study *International Journal of Prosthodontics* **19(5)** 504-506.

33. Valandro LF, Baldissara P, Galhano GAP, Melo RM, Mallmann A, Scotti R, & Bottino MA (2007) Effect of mechanical cycling on the push-out bond strength of fiber posts adhesively bonded to human root dentin *Operative Dentistry* **32(6)** 579-588.

34. Colosimo EA, & Giolo SR (2006) *Survival Analysis Applied* Edgard Blücher Ltd, Sao Paulo, Brazil.

35. Caplan DJ, Kolker J, Rivera EM, & Walton RE (2002) Relationship between number of proximal contacts and survival of root canal treated teeth *International Endodontic Journal* **35(2)** 193-199.

36. Wegner PK, Freitag S, & Kern M (2006) Survival rate of endodontically treated teeth with posts after prosthetic restoration *Journal of Endodontics* **32(10)** 928-931.

37. Schmitter M, Rammelsberg P, Gabbert O, & Ohlmann B (2007) Influence of clinical baseline findings on the survival of 2 post systems: a randomized clinical trial *International Journal of Prosthodontics* **20(2)** 173-178.

38. Schmitter M, Hamadi K, & Rammelsberg P (2011) Survival of two post systems: five-year results of a randomized clinical trial *Quintessence International* **42(10)** 843-850.

39. Magne P, & Knezevic A (2009) Thickness of CAD-CAM composite resin overlays influences fatigue resistance of endodontically treated premolars *Dental Materials* **25(10)** 1264-1268.

40. Bitter K, Noetzel J, Stamm O, Vaudt J, Meyer-Lueckel H, Neumann K, & Kielbassa AM (2009) Randomized clinical trial comparing the effects of post placement on failure rate of postendodontic restorations: preliminary results of a mean period of 32 months *Journal of Endodontics* **35(11)** 1477-1482.

41. Piovesan EM, Demarco FF, Cenci MS, & Pereira-Cenci T (2007) Survival rates of endodontically treated teeth restored with fiber-reinforced custom posts and cores: a 97-month study *International Journal of Prosthodontics* **20(6)** 633-639.

42. Signore A, Kaitsas V, Ravera G, Angiero F, & Benedicenti S (2011) Clinical evaluation of an oval-shaped prefabricated glass fiber post in endodontically treated premolars presenting an oval root canal cross-section: a retrospective cohort study *International Journal of Prosthodontics* **24(3)** 255-263.

43. Zicari F, Van Meerbeek B, Debels E, Lesaffre E, & Naert I (2011) An up to 3-year controlled clinical trial comparing the outcome of glass fiber posts and composite cores with gold alloy-based posts and cores for the restoration of endodontically treated teeth *International Journal of Prosthodontics* **24(4)** 363-372.

44. Soares CJ, Pizi EC, Fonseca RB, & Martins LR (2005) Influence of root embedment material and periodontal ligament simulation on fracture resistance tests *Brazilian Oral Research* **19(1)** 11-16.

45. Amaral M, Favarin Santini M, Wandscher V, Villaça Zogheib L, & Valandro LF (2009) Effect of coronal macroretentions and diameter of a glass-FRC on fracture resistance of bovine teeth restored with fiber posts *Minerva Stomatologica* **58(3)** 99-106.

46. Santini MF, Wandscher V, Amaral M, Baldissara P, & Valandro LF (2011) Mechanical cycling on teeth restored with fiber posts: impact of coronal grooves and diameter of glass fiber post on fracture resistance *Minerva Stomatologica* **60(10)** 485-493.

47. Wiskott HWA, Nicholls JL, & Belser, UC (1995) Stress fatigue: basic principles and prosthodontic implications *International Journal of Prosthodontics* **8(2)** 105-116.

48. Ni CW, Chang CH, Chen TY, & Chuang SF (2010) A multiparametric evaluation of post-restored teeth with simulated bone loss *Journal of the Mechanical Behavior of Biomedical Materials* **4(3)** 322-330.

49. Özcan M, & Valandro LF (2009) Fracture strength of endodontically-treated teeth restored with post and cores and composite cores only *Operative Dentistry* **34(4)** 429-436.

50. Al-Omiri MK, Mahmoud AA, Rayyan MR, & Abu-Hammad O (2010) Fracture resistance of teeth restored with post-retained restorations: an overview *Journal of Endodontics* **36(9)** 1439-1449.

51. Sahafi A, Peutzfeldt A, Asmussen E, & Godtfredsen K (2004) Retention and failure morphology of prefabricated posts *International Journal of Prosthodontics* **17(3)** 307-312.

52. Sahafi A, Peutzfeldt A, Ravnholt G, Asmussen E, & Gotfredsen K (2005) Resistance to cyclic loading of teeth restored with posts *Clinical Oral Investigations* **9(2)** 84-90.

53. Assif D, & Gorfil C (1994) Biomechanical considerations in restoring endodontically treated teeth *Journal of Prosthetic Dentistry* **71(6)** 565-567.

54. Kishen A, Kumar GV, & Chen NN (2004) Stress-strain response in human dentine: rethinking fracture predilection in postcore restored teeth *Dental Traumatology* **20(2)** 90-100.

55. Pereira JR, de Ornelas F, Conti PC, & do Valle AL (2006) Effect of a crown ferrule on the fracture resistance of endodontically treated teeth restored with prefabricated posts *Journal of Prosthetic Dentistry* **95(1)** 50-54.

56. Pereira JR, do Valle AL, Shiratori FK, Ghizoni JS, & Mello MP (2009) Influence of intraradicular post and crown ferrule on the fracture strength of endodontically treated teeth *Brazilian Dental Journal* **20(4)** 297-302.

57. Martelli H Jr, Pellizzer EP, Rosa BT, Lopes MB, & Gonini A Jr (2008) Fracture resistance of structurally compromised root filled bovine teeth restored with accessory glass fibre posts *International Endodontic Journal* **41(8)** 685-692.

58. Spazzin AO, Galafassi D, de Meira-Júnior AD, Braz R, & Garbin CA (2009) Influence of post and resin cement on stress distribution of maxillary central incisors restored with direct resin composite *Operative Dentistry* **34(2)** 223-229.

59. Mezzomo LA, Corso L, Marczak RJ, & Rivaldo EG (2011) Three-dimensional FEA of effects of two dowel-and-core approaches and effects of canal flaring on stress distribution in endodontically treated teeth *Journal of Prosthodontics* **20(2)** 120-129.

60. Pegoretti A, Fambri L, Zappini G, & Bianchetti M (2002) Finite element analysis of a glass fibre reinforced composite endodontic post *Biomaterials* **23(13)** 2667-2682.

61. Asmussen E, Peutzfeldt A, & Sahafi A (2005) Finite element analysis of stresses in endodontically treated, dowel-restored teeth *Journal of Prosthetic Dentistry* **94(4)** 321-329.

62. Akkayan B, & Gülmez T (2002) Resistance to fracture of endodontically treated teeth restored with different post systems *Journal of Prosthetic Dentistry* **87(4)** 431-437.

63. Beer FP, & Johnston R Jr (1994) *Vector Mechanics for Engineers Statics* Makron Books, Sao Paulo, Brazil.

64. Hibbeler RC (2006) *Mechanics of Materials* Pearson/ Prentice Hall, Sao Paulo, Brazil.