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Original Article

Fracture Resistance of Endodontically Treated Teeth Filled with Bioceramic-Based Root Canal Sealers Following Chelation with EDTA or Citric Acid

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CLINICAL SIGNIFICANCE

The marked reduction in fracture resistance of prepared but unobturated teeth highlights the clinical importance of the interappointment period in multi-visit endodontic treatments. Although bioceramic-based sealers may contribute to fracture resistance, preservation of tooth structure remains essential for maintaining durability.

ABSTRACT

Objective: The aim of this in vitro study was to evaluate the fracture resistance of teeth filled with bioceramic-based root canal sealers (BioRoot Flow and TotalFill BC Sealer) following chelation with EDTA or citric acid, and to assess the influence of different storage periods (1 and 3 months) on this outcome.

Materials and Methods: A total of 200 extracted single-rooted mandibular-premolars were used in the study. The samples were divided into 8 experimental-groups (n = 20) and 2 control-groups (n = 20). No procedure was performed in the negative control-group, whereas in the positive control-group, root canal preparation was performed but no obturation was applied. The experimental groups were established according to the type of chelating agent and sealer used, and after obturation, the specimens were stored for either 1 or 3 months. Fracture resistance testing was carried out using a universal-testing-machine. The data were statistically analysed.

Results: The highest fracture resistance was observed in the negative control-group, while the lowest value was obtained in the positive control-group. No statistically significant differences were found among the experimental-groups in terms of sealer-type, chelating-agent, or storage period ($p > 0.05$).

Conclusion: Prepared but unobturated teeth showed the lowest fracture resistance. This finding indicates that teeth may be more susceptible to fracture during the interappointment period in multi-visit endodontic treatments. In addition, although bioceramic-based sealers increased fracture resistance, they did not restore it to the level of intact teeth.

1. Introduction

Vertical root fractures are among the most serious complications encountered after endodontic treatment. The prognosis is generally poor, particularly in single-rooted teeth, and often results in tooth extraction.[1] Factors affecting root fracture following endodontic treatment include excessive instrumentation, post-treatment dehydration of dentin, and uncontrolled pressure applied during obturation. All of these factors may cumulatively increase the risk of root fracture when combined with occlusal loading. In addition, the synergistic effects of intracanal irrigants and medicaments may alter the physical and mechanical properties of root dentin, potentially leading to failure or fracture of endodontically treated teeth.[2,3] Therefore, the development of strategies aimed at enhancing tooth strength during root canal treatment is of great importance.

Root canal irrigation solutions play a supportive role in mechanical instrumentation by facilitating the removal of pulp remnants and the smear layer formed after preparation. Elimination of the smear layer allows the opening of dentinal tubules, thereby increasing the contact of root canal filling materials and sealers with the canal walls and improving their penetration into the dentinal tubules.[4,5] Chelating agents are widely used solutions for smear layer removal. Among these agents, 17% EDTA and citric acid (CA) are frequently preferred due to their high effectiveness in removing the smear layer. EDTA is a strong chelating agent capable of dissolving the inorganic components of the smear layer and opening dentinal tubules.[6] CA, on the other hand, reduces the calcium content of dentin, increases permeability, and demonstrates a smear layer removal efficacy comparable to that of EDTA.[7,8] However, the demineralizing effects of chelating agents on dentin are not limited to smear layer removal; they may also affect the chemical and mechanical properties of dentin. The removal of inorganic components from the dentin structure can lead to a decrease in dentin microhardness and greater exposure of the collagen matrix, which may influence the fracture resistance of root dentin. Therefore, irrigation protocols should be carefully balanced to ensure effective smear layer removal while minimizing adverse effects on the fracture resistance of root dentin.[7,8]

In recent years, bioceramic-based root canal sealers have gained prominence due to their high biocompatibility and biological activity. Clinical studies have confirmed that, following proper root canal cleaning and shaping, root canal treatment performed with a bioceramic-based sealer and gutta-percha is a safe and predictable treatment method with high clinical success rates.[9] These sealers enhance adhesion by forming a chemical bond at the interface between dentin and the filling material, reduce microleakage, and demonstrate the potential to reinforce root canal walls. Furthermore, it has been reported that bioceramic sealers promote hydroxyapatite formation at the sealer–dentin interface, which may contribute to the mechanical strength of the root structure.[10]

TotalFill BC Sealer (TF; FKG, La Chaux-de-Fonds, Switzerland) and BioRoot Flow (BRF; Septodont, Saint-Maur-des-Fossés, France) are among the widely used bioceramic-based sealers in clinical practice. TF is a premixed, calcium silicate–based root canal sealer that sets in the presence of moisture. This property allows it to utilize residual moisture within the canal environment to achieve complete setting. It contains biocompatible components such as calcium silicates, calcium phosphate, and zirconium oxide, and exhibits antibacterial

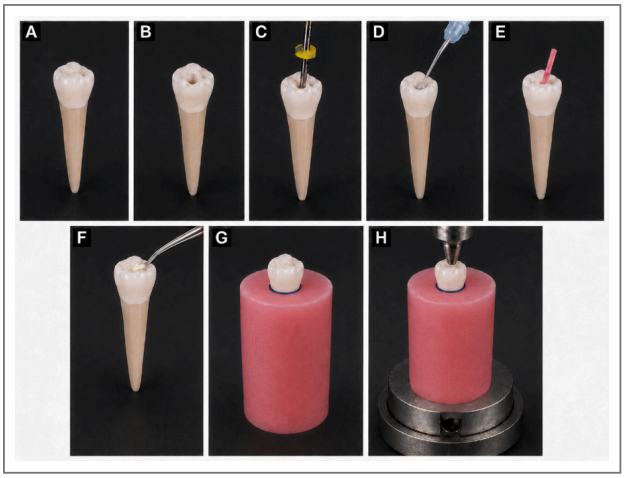

Figure 1. Figure 1. Sample preparation and fracture resistance testing procedure. A: Intact tooth sample; B: Tooth sample with Class I cavity preparation; C: Root canal preparation; D: Root canal irrigation (EDTA or citric acid); E: Root canal obturation (BioRoot Flow/gutta-percha or TotalFill BC Sealer/gutta-percha); F: Composite resin restoration; G: Placement of the sample in an acrylic block and simulation of the periodontal ligament space; H: Fracture resistance testing of the sample. (This figure is a representative illustration prepared to schematically demonstrate the experimental procedure steps.)

activity by generating a high pH during the setting reaction. TF has been reported to provide deep penetration into dentinal tubules, demonstrate volumetric stability, and ensure long-term sealing ability due to the absence of shrinkage after setting.[11] In addition, its premixed formulation provides a standardized consistency, eliminating mixing errors and offering ease of use in clinical applications.[12] BRF is the premixed formulation of BioRoot RCS (BR; Septodont, Saint-Maur-des-Fossés, France), recently introduced to the market by the manufacturer. According to the manufacturer, BRF retains all the desirable physicochemical properties of BR, including high biocompatibility, bioactivity, and immunomodulatory potential.[13] Owing to its lower viscosity and non–water-based carrier system, BRF —similar to many premixed bioceramic sealers—can be used with both cold and warm obturation techniques.[14]

A review of the literature reveals that several studies have investigated the effects of storage period, final irrigation solution, and obturation technique on the fracture resistance of teeth filled with different bioceramic-based root canal sealers.[5,15–17] Considering the combined influence of different storage periods of bioceramic sealers and the effects of chelating agents used in root canal irrigation on dentin structure, the interaction of these variables may have clinically relevant implications for root fracture resistance. However, studies evaluating these factors together remain limited, and this topic has not yet been sufficiently investigated within a comprehensive experimental design including storage period, type of chelating agent, and type of sealer. Moreover, to the best of our knowledge, evidence regarding the effect of BioRoot Flow (BRF), a recently introduced bioceramic-based sealer, on the fracture resistance of teeth is still limited. Therefore, further investigation of BRF in this context may provide valuable insight into its potential contribution to the reinforcement of endodontically treated teeth. Therefore, the aim of this in vitro study was to evaluate the fracture resistance of teeth filled with bioceramic-based root canal sealers (BioRoot Flow and TotalFill BC Sealer) following chelation with EDTA or citric acid, and to assess the influence of different storage periods (1 and 3 months) on this outcome. The null hypotheses of this study were that: the type of bioceramic root canal sealer (BioRoot Flow vs. TotalFill BC Sealer), the type of chelating agent used for final irrigation (17% EDTA vs. 10% citric acid), and the storage period (1 month vs. 3 months) would have no statistically significant effect on the fracture resistance of endodontically treated teeth, either individually or through their mutual interactions.

Table 1. Endodontic study groups table

Study groups	Sealer Type	Chelating Agent	Storage period	n
Negative Control	—	—	—	20
Positive Control	—	—	—	20
BRF / CA / 1 month	BioRoot Flow	CA	1 month	20
BRF / CA / 3 months	BioRoot Flow	CA	3 months	20
BRF / EDTA / 1 month	BioRoot Flow	EDTA	1 month	20
BRF / EDTA / 3 months	BioRoot Flow	EDTA	3 months	20
TF / CA / 1 month	TotalFill BC Sealer	CA	1 month	20
TF / CA / 3 months	TotalFill BC Sealer	CA	3 months	20
TF / EDTA / 1 month	TotalFill BC Sealer	EDTA	1 month	20
TF / EDTA / 3 months	TotalFill BC Sealer	EDTA	3 months	20

Note. BRF: BioRoot Flow, TF: TotalFill BC Sealer, CA: Citric Acid, EDTA: Ethylenediaminetetraacetic Acid, n: Number of specimens

2. Materials and Methods

2.1. Ethical Approval and Sample Size Calculation

This study was approved by the Mersin University Clinical Research Ethics Committee (protocol no. 2026/08, dated 07.01.2026). According to the power analysis performed using the GPower program (GPower 3.1 software; Heinrich Heine University, Düsseldorf, Germany), for a study design including 10 groups and analyzed with F test: ANOVA (fixed effects, special, main effects and interactions), with a significance level (α) of 0.05, an effect size (w) of 0.33, and a statistical power (1–β) of 0.95, it was determined that a minimum total sample size of 200 specimens was required, corresponding to 20 specimens per group.[18]

2.2. Selection and Preparation of Teeth

In this study, a total of 200 permanent single-rooted and single-canaled mandibular premolar teeth, extracted for orthodontic and periodontal reasons, were used to evaluate the effect of different calcium silicate-based repair materials on the fracture resistance of teeth. The teeth were disinfected with 2.5% sodium hypochlorite (NaOCl) (Wizard, NaOCl, Rehber Kimya, İstanbul, Türkiye) solution and stored in distilled water. Periapical radiographs were taken in both buccolingual and mesiodistal directions to evaluate the presence of calcification, internal resorption, or additional root canals. Teeth found to have caries, calcified canals, root resorption, fractures, or cracks on radiographic examination were excluded from the study. To standardize the samples, the mesiodistal and buccolingual diameters at the cementoenamel junction (CEJ) were measured using a digital caliper, and teeth exhibiting marked morphological differences were excluded from the study. Teeth with a root length of 15 ± 1 mm were included in the study. Then, an endodontic access cavity was prepared in each tooth included in the study. A #15 K-type stainless steel hand file (Mani Inc., Tochigi-Ken, Japonya) was inserted into the root canals to check the canal patency. Teeth with straight, single canals that could be negotiated to the apex were included in the study. Teeth with multiple canals, calsified canals, or previous root canal treatment were excluded.

The root canals were instrumented using a nickel–titanium rotary file system (Smart Gold, Endoart, İnci Dental, Istanbul, Türkiye) in accordance with the manufacturer's instructions. Canal preparation was performed to the working length using 15/.04, 20/.04, and 25/.04 files sequentially. During preparation, irrigation was performed with 2 mL of 2.5% sodium hypochlorite (NaOCl) (Wizard NaOCl, Rehber Kimya, Istanbul, Türkiye) using a 30-G side-vented needle (Cerkamed, Poland) after each file change. After completion of root canal preparation, each tooth was assigned a unique identification number to ensure tracking throughout the study. The numbered specimens were then randomly

Table 2. Comparison of fracture resistance values according to the study groups

	n	Mean	Standard Deviation (SD)	Median	Min	Max	F	p
Negative Control [b]	20	1085.84	248.85	1162.96	586.58	1446.25	13.052	<0.001*
Positive Control [c]	20	237.02	106.99	246.54	94.25	468.98		
BRF / EDTA / 1 month[a]	20	783.76	267.75	795.13	255.62	1216.39		
BRF / EDTA / 3 months[a]	20	759.46	273.35	695.73	374.54	1270.42		
BRF / CA / 1 month[a]	20	824.98	286.03	878.25	302.82	1427.44		
BRF / CA / 3 months [a]	20	764.96	245.3	803.17	354.33	1155.44		
TF / EDTA / 1 month[a]	20	795.31	280.48	794.21	255.03	1306.09		
TF / EDTA / 3 months[a]	20	851.66	168.73	810.35	584.03	1136.58		
TF / CA / 1 month[a]	20	737.25	225.01	729.8	246.02	1248.04		
TF / CA / 3 months[a]	20	745.79	390.82	663.29	250.22	1969.29		

Note. n: Number of samples, Mean: Mean value, SD: Standard Deviation, Min.: Minimum, Max.: Maximum, F: Anova value, p: significance level. Different superscript lowercase letters indicate statistically significant differences among the groups ($p < 0.05$). Groups sharing the same superscript letter are not significantly different from each other.

allocated to the positive control group and to the experimental groups formed according to the chelating agent used (EDTA or citric acid), the bioceramic-based sealer type (BioRoot Flow or TotalFill BC Sealer), and the storage period (1 month or 3 months). After group allocation, the final irrigation protocol was performed in the experimental groups according to the assigned chelating agent as follows:

6 mL of 2.5% NaOCl (Wizard NaOCl, Rehber Kimya, Istanbul, Türkiye),

Followed by 6 mL of either 17% EDTA (Cerkamed, Poland) or 10% citric acid solution (Sigma-Aldrich, St. Louis, MO, USA), according to the respective experimental group, for 1 minute to ensure smear layer removal.[6,7]

Finally, 5 mL of distilled water (Bufarma Distile Su, Bufarma Biyomedikal, Ankara, Türkiye) was applied to remove residual irrigants.

Following irrigation, the root canals were completely dried with paper points (Pearl Endo Paper Points, Vietnam). The canals of the teeth assigned to the experimental groups were obturated using the designated bioceramic-based sealer (TF or BRF) in combination with gutta-percha cones (25/.04) (Pearl Endo Gutta Percha, Vietnam) employing the single-cone technique. The quality of the root canal filling was verified radiographically in both buccolingual and mesiodistal directions to confirm adequate filling length, homogeneity, and the absence of voids or overextension. Specimens with inadequate obturation quality were excluded and replaced. After completion of the root canal filling, the access cavities were restored with a composite resin restorative material (Charisma Smart, Heraeus Kulzer GmbH, Hanau, Germany). Prior to fracture resistance testing, all experimental groups were stored in an incubator at 37 °C and 100% humidity according to their designated storage periods (1 month and 3 months).

2.3. Study Groups

The teeth were randomly assigned into two main experimental groups (n = 80 each) according to the material used, and two control groups (n = 20 each). Each main experimental group was further subdivided into four subgroups (n = 20) based on storage periods (1 month and 3 months) and type of chelating agent (EDTA and CA). The control groups were designated as a positive control group (n = 20) and a negative control group (n = 20) (Table 1).

Control Groups

Negative Control (n = 20): Intact teeth with no root canal procedures performed.

Positive Control (n = 20): Teeth in which the access cavity was prepared and root canal instrumentation was completed, but no root canal filling was performed.

Experimental Groups

BRF / CA / 1 month (n = 20): Following root canal preparation, citric acid was used as the chelating agent; canals were filled with BioRoot Flow and specimens were allowed to set for 1 month.

BRF / CA / 3 months (n = 20): After root canal preparation, irrigation with citric acid was performed; canals were filled with BioRoot Flow and specimens were allowed to set for 3 months.

BRF / EDTA / 1 month (n = 20): Following root canal preparation, irrigation with EDTA was performed; canals were filled with BioRoot Flow and specimens were allowed to set for 1 month.

BRF / EDTA / 3 months (n = 20): After root canal preparation, EDTA irrigation was applied; canals were filled with BioRoot Flow and specimens were allowed to set for 3 months.

TF / CA / 1 month (n = 20): Following root canal preparation, irrigation with citric acid was performed; canals were filled with TotalFill BC Sealer and specimens were allowed to set for 1 month.

TF / CA / 3 months (n = 20): After root canal preparation, citric acid irrigation was performed; canals were filled with TotalFill BC Sealer and specimens were allowed to set for 3 months.

TF / EDTA / 1 month (n = 20): Following root canal preparation, irrigation with EDTA was performed; canals were filled with TotalFill BC Sealer and specimens were allowed to set for 1 month.

TF / EDTA / 3 months (n = 20): After root canal preparation, EDTA irrigation was applied; canals were filled with TotalFill BC Sealer and specimens were allowed to set for 3 months.

2.4. Periodontal Ligament Simulation

To simulate the periodontal ligament space, each tooth root was immersed into warm wax starting 1 mm below the CEJ until a wax thickness of 0.3 mm was achieved. Once the desired thickness was obtained, the teeth were vertically embedded into self-curing acrylic resin blocks, with 14 mm of the root remaining in the resin, positioned 1 mm below the CEJ to simulate biological width. The wax was then melted to create a 0.3 mm thick negative space between the root surface and the acrylic resin block. This space was then filled with silicone impression material, starting 1 mm below the CEJ and covering the entire root surface, to simulate the periodontal ligament.

2.5. Fracture Resistance Testing

The fracture resistance test was performed using a universal testing machine (Besmak, Ankara, Turkey) at a loading speed of 1 mm/min. Before testing, the universal testing machine was calibrated according to the manufacturer's instructions, and the testing parameters were verified. A stainless-steel tip (tip diameter = 3 mm) was positioned perpendicular to the long axis of the tooth, and a compressive load was applied vertically along the long axis of the tooth at a rate of 1 mm/min until fracture occurred. All fracture resistance tests were performed by a single trained operator using the same device settings, loading speed, stainless-steel tip, and specimen positioning protocol. The operator performing the fracture resistance test was blinded to the allocation of the experimental subgroups, including the chelating agent, bioceramic-based sealer type, and storage period. Although the negative and positive control groups were identifiable due to the nature of the methodology, the operator was not informed about the specific allocation of the experimental specimens. The experimental workflow

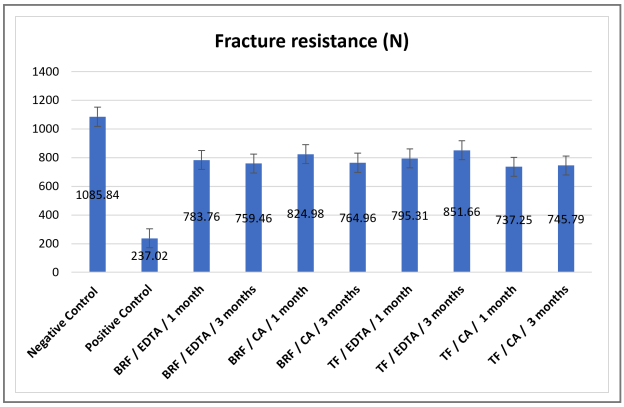

Figure 2. Fracture resistance mean values

for specimen preparation and fracture resistance testing is illustrated in Figure 1. The maximum force required to fracture each tooth was automatically recorded in Newtons (N) by the testing software and subsequently transferred to a Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) file to minimize manual recording errors.

2.6. Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics version 27 (IBM Corp., Armonk, NY, USA). The normality of the data distribution was assessed using the Shapiro–Wilk test. Independent samples t-test and one-way ANOVA were used to compare fracture resistance values. When significant differences were detected, pairwise comparisons were performed using the Bonferroni post hoc test. The Fisher–Freeman–Halton Exact test was used to compare the distribution of fracture modes among the groups. The level of statistical significance was set at $p < 0.05$.

3. Results

A statistically significant difference was found among the groups in terms of fracture resistance values ($F = 13.052$; $p < 0.001$). The negative control group demonstrated significantly higher fracture resistance compared to all other groups ($p < 0.05$), whereas the positive control group showed significantly lower values than all other groups ($p < 0.05$). The highest mean fracture resistance was observed in the negative control group (1085.84 ± 248.85 N), while the lowest mean value was obtained in the positive control group (237.02 ± 106.99 N).

When evaluated according to sealer type, no statistically significant difference was found between the BRF and TF groups ($p > 0.05$). In the BRF groups, the mean fracture resistance values ranged from 759.46 to 824.98 N, whereas in the TF groups, the values ranged from 737.25 to 851.66 N. Among the experimental groups, the highest mean fracture resistance was observed in the TF / EDTA / 3 months group (851.66 ± 168.73 N), while the lowest mean value was recorded in the TF / CA / 1 month group (737.25 ± 225.01 N). However, no statistically significant difference was detected based on sealer type ($p=0.446$).

When evaluated in terms of chelating agent type, no statistically significant difference was found between the EDTA and CA groups with respect to fracture resistance values ($p > 0.05$). Although the mean fracture resistance values were generally higher in the EDTA-treated groups compared to the CA groups, this increase did not reach statistical significance.

Regarding storage period (1 month vs. 3 months), no statistically significant differences were observed between identical combinations of sealer type and chelating agent ($p > 0.05$). When the subgroups were evaluated separately in terms of storage period, a decrease in fracture resistance was observed in the BRF / EDTA group at 3 months (759.46 N) compared to 1 month (783.76 N). Similarly, in the BRF / CA group, fracture resistance decreased at 3 months (764.96 N) compared to 1 month (824.98 N). In contrast, the TF / EDTA group demonstrated an increase in fracture resistance at 3 months (851.66 N) compared to 1 month (795.31 N). A slight increase was also observed in the TF / CA group at 3 months (745.79 N) compared to 1 month (737.25 N).

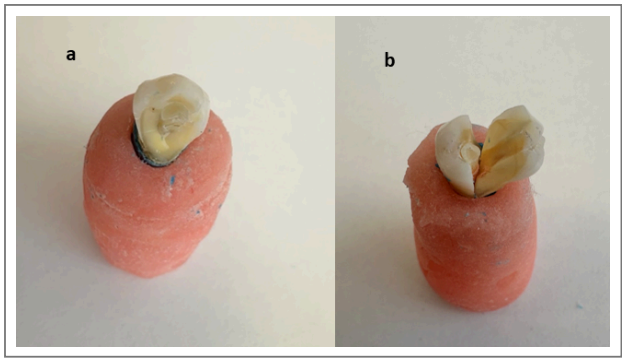

Figure 3. Mode of fracture. Restorable fracture mode (a), Non-restorable fracture mode (b)

However, none of these changes were statistically significant ($p > 0.05$) (Table 2) (Fig. 2).

3.1. Modes of fracture

Fractures were classified as “restorable” when the fracture line was located above the acrylic resin level, and as “unrestorable” when the fracture extended below the cementoenamel junction (CEJ) (Fig. 3, Table 3).[16] When all groups were evaluated collectively, 47 out of 200 specimens (23.5%) exhibited restorable fractures, whereas 153 specimens (76.5%) demonstrated unrestorable fractures. A statistically significant difference was found among the groups in terms of fracture mode distribution (Fisher–Freeman–Halton Exact Test = 21.494; $p = 0.007$). This significance was attributed to the absence of restorable fractures in the positive control group ($n = 0$). No statistically significant difference was detected among the percentage distributions of the remaining groups ($p > 0.05$). In the negative control group, the rate of restorable fractures was 35% ($n = 7$), whereas in the positive control group, all specimens (100%, $n = 20$) exhibited unrestorable fractures. Among the experimental groups, the highest rates of restorable fractures were observed in the TF / CA / 1 month (45%, $n = 9$) and TF / CA / 3 months (40%, $n = 8$) groups. The lowest rates were recorded in the BRF / EDTA / 1 month (10%, $n = 2$) and TF / EDTA / 3 months (10%, $n = 2$) groups.

4. Discussion

The present study aimed to evaluate the effects of different chelating agents, bioceramic-based root canal sealers, and storage periods on the fracture resistance of endodontically treated teeth. According to the study findings, only the negative control group exhibited significantly higher fracture resistance compared with the other groups ($p < 0.05$). Among all groups, the lowest fracture resistance values were observed in the positive control group. When the experimental groups were compared with each other, no statistically significant differences were found in terms of storage period, sealer type, or chelating agent used ($p > 0.05$). These findings support the null hypothesis of the present study.

Fracture resistance is a fundamental parameter for evaluating the mechanical behavior of teeth under functional loads following endodontic and restorative treatments. Irrigation protocols applied during root canal treatment and the filling materials used may affect the structural integrity of dentin; in particular, reductions in dentin thickness and chemically induced alterations can render the tooth more susceptible to fracture.[19] Therefore, fracture resistance tests are widely employed to objectively assess the effects of different materials and treatment protocols on the mechanical performance of teeth.

Although in vitro fracture tests do not fully replicate clinical conditions, they provide an important experimental model by allowing comparisons between groups under standardized and controlled conditions. In fracture resistance studies, the type of tooth selected and the direction of the applied force are critical factors that directly influence the results.[20] In the present study, mandibular premolar teeth were preferred due to their anatomical characteristics, which make them more suitable for vertical loading. The load was applied perpendicular to the long axis of the tooth (vertical loading). This approach facilitated the standardization of the applied force and

Table 3. Mode of fracture for all group

	Restorable n%	Non-restorable n%	Total n%	Fisher-Freeman-Halton Exact Test	p
Negative Control	7 35%	13 65%	20 100%		
Positive Control	0 0%	20 100%	20 100%		
BRF / EDTA / 1 month	2 10%	18 90%	20 100%		
BRF / EDTA / 3 months	5 25%	15 75%	20 100%		
BRF / CA/ 1 month	4 20%	16 80%	20 100%		
BRF / CA / 3 months	6 30%	14 70%	20 100%	21.494	0.007*
TF / EDTA / 1 month	4 20%	16 80%	20 100%		
TF / EDTA / 3 months	2 10%	18 90%	20 100%		
TF / CA / 1 month	9 45%	11 55%	20 100%		
TF / CA / 3 months	8 40%	12 60%	20 100%		

Note. n: Number of samples, p: <0.05

contributed to achieving a similar stress distribution among all specimens. Thus, it was intended to obtain more reliable and comparable results.

When the results of the present study are considered, the significantly higher fracture resistance observed in the intact tooth group (negative control group) compared with all other groups is clinically important. This finding highlights the critical role of preserving tooth structural integrity and demonstrates the weakening effect of access cavity preparation and canal instrumentation on root dentin. In agreement with the present findings, Alkahtany et al. reported that the group consisting of intact teeth showed the highest fracture resistance values (946.61 ± 166.465 N), whereas the instrumented but unfilled group exhibited the lowest fracture resistance values (433.31 ± 129.350 N).[21] These findings support the interpretation that tooth structure loss and reduced internal dentinal support following endodontic access cavity preparation and canal instrumentation may increase susceptibility to fracture. Therefore, the lowest fracture resistance values observed in the prepared but unobturated tooth group (positive control group) in the present study may be attributed to the absence of internal support that could be provided by root canal filling materials. This finding suggests that teeth may be more vulnerable to fracture during the interappointment period, particularly in multi-visit endodontic treatments. Therefore, in multi-visit endodontic treatments, the temporary coronal restoration should be carefully placed to ensure adequate sealing and mechanical stability during the interappointment period. Patients should also be advised to avoid excessive occlusal loading on the treated tooth during this period.

Chelating agents are widely used in root canal irrigation protocols to enhance the removal of the smear layer and to reduce the potential cytotoxic effects of sodium hypochlorite (NaOCl). In the present study, 17% EDTA and 10% citric acid were selected as final irrigation solutions, and their effects on tooth fracture resistance were evaluated. According to the results, the type of chelating agent used did not produce a statistically significant difference in fracture resistance ($p > 0.05$). This finding is consistent with a previous study that investigated the effect of chelating agents on fracture resistance and reported similar results.[16] However, a recent study reported that 10% citric acid showed the lowest fracture resistance values, whereas EDTA exhibited the highest values.[22] The discrepancy between these findings may mainly be attributed to methodological differences in study design. Factors such as the concentration of irrigation agents, duration of application, total contact time, and irrigation protocol (e.g., sequential use, activation method) can directly influence the mechanical properties of dentin.

In the present study, when the effect of storage period (1 month and 3 months) on fracture resistance was evaluated, the time factor did not produce a statistically significant difference in fracture resistance ($p > 0.05$). When the subgroups were analyzed separately, a decrease in mean fracture resistance at 3 months compared to 1 month was observed in the BRF / EDTA and BRF / CA groups. In contrast, a slight increase at 3 months was detected in the TF / EDTA and TF / CA groups. However, none of these changes were statistically significant ($p > 0.05$). These results indicate that the minor fluctuations observed over time may be related to ongoing biological and chemical interactions, but they do not result in clinically meaningful mechanical differences. The hydration and biomineralization reactions of calcium silicate–based materials may continue over time, strengthening the material–dentin interface and thereby contributing to an increase in tooth fracture resistance.[23] However, the findings of the present study showed that these reactions did not result in a statistically significant increase in fracture resistance within the 1–3 month period. The present findings are consistent with the study by Özyürek and Türker, who evaluated the effect of 1-week and 1-month storage periods on the fracture resistance of roots filled with AH 26, MTA Plus Sealer, and BioRoot RCS. They reported that storage time did not significantly affect fracture resistance values, supporting the view that short-term storage periods may not produce meaningful mechanical changes in root-filled teeth.[24] Similarly, Elfaramawy and Abdelrahman evaluated the fracture resistance of endodontically treated teeth filled with different root canal sealers after 1 week, 2 weeks, and 1 month of storage and reported that elapsed time did not significantly influence fracture resistance.[25] These findings are consistent with and support the results of the present study. However, conflicting findings have also been reported in the literature. Smran et al. evaluated the effect of thermomechanical cyclic aging on the fracture resistance of premolars obturated with AH Plus and BioRoot RCS.[26] In their study, the specimens were subjected to thermal cycling and dynamic loading protocols simulating approximately 1.5 and 3 years of clinical function. The authors reported that fracture resistance significantly decreased in both the AH Plus and BioRoot RCS groups as the thermomechanical aging period increased. This difference from the present study may be attributed to the use of thermomechanical cycling, dynamic loading simulating masticatory forces, longer-term clinical aging protocols, and differences in experimental conditions.

When the findings of the present study were evaluated in terms of root canal sealer type, no statistically significant difference was found in fracture resistance between the BRF and TF BC Sealer groups ($p > 0.05$). This finding suggests that, under standardized experimental conditions, the two different bioceramic-based root canal sealers exhibited similar mechanical behavior and that sealer type alone did not have a decisive effect on fracture resistance. Similar to the findings of the present study, Ismail et al. evaluated the effects of BioRoot RCS, TotalFill BC, and AH Plus root canal sealers on the fracture resistance of root dentin under different irrigation protocols and reported no statistically significant difference among the tested sealers.[27] This finding supports the view that calcium silicate/bioceramic-based sealers such as BioRoot and TotalFill may exhibit comparable mechanical performance in terms of fracture resistance. In contrast, Muraleedhar et al. compared the effects of AH Plus, BioRoot RCS, and MTA Fillapex root canal sealers on the fracture resistance of root dentin. In their study, the highest fracture resistance was reported in the resin-based AH Plus group, followed by BioRoot RCS and MTA Fillapex. Furthermore, when the bioceramic/calcium silicate–based sealers were evaluated separately, BioRoot RCS showed significantly higher fracture resistance than MTA Fillapex.[28] These differences among studies may be attributed to variations in the physicochemical properties, material compositions, bonding mechanisms to dentin, and setting behaviors of the tested sealers. In addition, methodological differences such as tooth type, specimen preparation protocol, irrigation procedure, obturation

technique, storage period, and loading conditions may have directly influenced the fracture resistance outcomes.

In the present study, the most frequently observed fracture pattern was an unrestorable fracture occurring in the buccolingual direction. This finding is consistent with a previous fracture resistance study.[16] The predominance of unrestorable vertical fractures may be explained by the transmission of the applied load parallel to the long axis of the tooth, resulting in stress accumulation along the root. The prognosis of such fractures is generally poor and, in most cases, extraction of the tooth is required.[29] In contrast, another study reported that the majority of fractures were classified as "restorable".[30] The differences in fracture patterns and rates observed among studies are most likely attributable to variations in experimental methodologies, specimen preparation procedures, and the types of teeth evaluated. Since loading protocols, material selection, and simulated clinical conditions may differ across studies, variations in outcomes are expected.

Although the findings of the present study provide valuable insights, several limitations should be considered. First, the study was conducted under in vitro conditions; therefore, intraoral factors such as dynamic masticatory forces, temperature fluctuations, moisture balance, and biological influences could not be fully simulated. This limits the direct generalization of the results to clinical practice. Second, the study evaluated short-term fracture resistance (1 month and 3 months) and did not provide information regarding long-term biomechanical durability or material–dentin interactions. In particular, potential material degradation over time and structural changes in dentin were not assessed. Third, vertical loading was applied during the fracture resistance test. However, under clinical conditions, traumatic forces are often oblique rather than parallel to the long axis of the tooth. Therefore, the use of only vertical loading may not fully reflect the direction of traumatic forces encountered clinically, representing another limitation of the study. Fourth, only single-rooted mandibular premolar teeth were included. Teeth with different anatomical characteristics may exhibit different biomechanical behaviors. Variations in root number, root morphology, canal width, dentin thickness, and root cross-sectional shape among different tooth types may influence fracture resistance outcomes. Accordingly, the findings of this study are applicable only to single-rooted premolars, and caution should be exercised when extrapolating the results to teeth with different anatomical features. For these reasons, further long-term and clinical studies are needed to support and validate the generalizability of the present findings.

5. Conclusion

Within the limitations of this in vitro study, prepared but unobturated teeth were found to be more susceptible to fracture, highlighting the clinical importance of the interappointment period in multi-visit endodontic treatments. Bioceramic-based root canal sealers contributed to increased fracture resistance compared with prepared but unobturated teeth; however, they did not restore resistance to the level of intact teeth. The comparable performance of the tested sealers, chelating agents, and storage periods suggests that fracture resistance is not determined solely by these factors. Therefore, preservation of tooth structure as much as possible, ensuring adequate sealing and mechanical stability of temporary restorations in multi-visit treatments, and planning an appropriate coronal restoration after treatment are essential for improving the biomechanical prognosis of endodontically treated teeth.

References

1. Liao WC, Chen CH, Pan YH, Chang MC, Jeng JH. Vertical root fracture in non-endodontically and endodontically treated teeth: current understanding and future challenge. *J Pers Med*. 2021;11(12):1375.
2. Patel S, Bhuva B, Bose R. Present status and future directions: vertical root fractures in root filled teeth. *Int Endod J*. 2022;55:804-826.
3. Prado M, Simão RA, Gomes BP. Effect of different irrigation protocols on resin sealer bond strength to dentin. *J Endod*. 2013;39(5):689-692.
4. Çobankara FK, Üngör M, Belli S. The effect of two different root canal sealers and smear layer on resistance to root fracture. *J Endod*. 2002;28(8):606-609.
5. Uzunoglu E, Yilmaz Z, Erdogan O, Görduysus M. Final irrigation regimens affect fracture resistance values of root-filled teeth. *J Endod*. 2016;42(3):493-495.
6. Ballal NV, Jain H, Rao S, Johnson AD, Baeten J, Wolcott JF. Evaluation of SmearOFF, maleic acid and two EDTA preparations in smear layer removal from root canal dentin. *Acta Odontol Scand*. 2019;77(1):28-32.
7. Qian W, Shen Y, Haapasalo M. Quantitative analysis of the effect of irrigant solution sequences on dentin erosion. *J Endod*. 2011;37(10):1437-1441.
8. Mankeliya S, Singhal RK, Gupta A, Pathak VK, Kushwah A. A comparative evaluation of smear layer removal by using four different irrigation solutions: an in vitro SEM study. *J Contemp Dent Pract*. 2021;22(5):527-531.
9. Bardini G, Casula L, Ambu E, Musu D, Mercadè M, Cotti E. A 12-month follow-up of primary and secondary root canal treatment in teeth obturated with a hydraulic sealer. *Clin Oral Investig*. 2021;25(5):2757-2764.
10. Al-Haddad A, Che Ab Aziz ZA. Bioceramic-based root canal sealers: a review. *Int J Biomater*. 2016;2016:9753210.
11. Almeida MM, Rodrigues CT, Matos AA, Carvalho KKT, Silva EJNL, Duarte MAH, et al. Analysis of the physicochemical properties, cytotoxicity and volumetric changes of AH Plus, MTA Fillapex and TotalFill BC Sealer. *J Clin Exp Dent*. 2020;12(11):e1058.
12. Kwak SW, Koo J, Song M, Jang IH, Gambarini G, Kim HC. Physicochemical properties and biocompatibility of various bioceramic root canal sealers: in vitro study. *J Endod*. 2023;49(7):871-879.
13. Sanz JL, López-García S, García-Bernal D, Rodríguez-Lozano FJ, Forner L, Lozano A, et al. Comparative bioactivity and immunomodulatory potential of the new Bioroot Flow and AH Plus Bioceramic sealer: an in vitro study on hPDLSCs. *Clin Oral Investig*. 2024;28(3):195.
14. Kim HI, Jang YE, Kim Y, Kim BS. Physicochemical changes in root-canal sealers under thermal challenge: a comparative analysis of calcium silicate- and epoxy-resin-based sealers. *Materials (Basel)*. 2024;17(8):1932.
15. Al-Hiyasat AS, Sawallha AM, Taha NA. The effect of sealer type and obturation technique on the fracture resistance of endodontically treated roots. *Clin Oral Investig*. 2023;27(12):7359-7367.
16. Akyüz İE, Düzgün S, Topçuoğlu HS. Effect of different irrigation solutions and coronal barrier materials used in regenerative endodontic treatment procedure on the fracture resistance of simulated open apexed maxillary central incisors: an in vitro study. *Odontology*. 2025;1-11.
17. Song Y, Kim KD, Jung BY, Park W, Pang NS. Comparative analysis of fracture resistance of endodontic sealer types and filling methods. *Materials (Basel)*. 2024;18(1):40.
18. Alskaf MKA, Achour H, Alzoubi H. The effect of Bioceramic HiFlow and EndoSequence bioceramic sealers on increasing the fracture resistance of endodontically treated teeth: an in vitro study. *Cureus*. 2022;14(12):e33051.
19. Cauwels RG, Lassila LV, Martens LC, Vallittu PK, Verbeeck RM. Fracture resistance of endodontically restored, weakened incisors. *Dent Traumatol*. 2014;30(5):348-355.

20. Gudapati S, Satish RK, Sajjan GS, Varma KM, Kumar VS, Kumar MS. Comparative evaluation of fracture resistance of simulated immature teeth restored with apical plugs of mineral trioxide aggregate, Biodentine, and bone cement: an in vitro study. *Endodontology*. 2023;35(1):30-34.
21. Alkahtany MF, Almadi KH, Alahmad FA, Alshehri AA, Alswayyed AA, Alzahran OM, et al. Influence of root canal sealers and obturation techniques on vertical root fracture resistance: an in vitro experiment. *Appl Sci*. 2021;11(17):8022.
22. Nikhade P, Tiwari S, Sudarshan C, Shetty P, Gupta NK. Impact of various irrigating agents on root fracture: an in vitro study. *J Contemp Dent Pract*. 2017;17(8):659-662.
23. Atmeh A, Chong E, Richard G, Festy F, Watson T. Dentin-cement interfacial interaction: calcium silicates and polyalkenoates. *J Dent Res*. 2012;91(5):454-459.
24. Özyürek EU, Türker SA. Evaluation of fracture resistance of roots filled with various root canal sealers at different time periods. *Eur Oral Res*. 2019;53(1):6-11.
25. Elfaramawy MT, Abdelrahman TY. The effect of bioceramic sealers on the fracture resistance of endodontically treated teeth: in vitro study. *Egypt Dent J*. 2021;67(1):857-860.
26. Smran A, Abdullah M, Ahmad NA, AL-Maflehi N, Samran A. Influence of thermal and mechanical load cycling on fracture resistance of premolars filled with calcium silicate sealer. *Appl Sci*. 2023;13(7):4388.
27. Ismail SM, Fayad D, Mohamed D, Eldaharawy M. Effect of two calcium-silicate and one resin sealers on the fracture resistance of root dentin using different treatments in dog's teeth: an in vivo study. *Dental Science Updates*. 2023;4(1):25-33.
28. Muraleedhar AV, Satish SV, Uthappa R, Patil AM, Gowda B. Comparative evaluation of the fracture resistance of roots after the application of three different root canal sealers: AH Plus, MTA Fillapex, and BioRoot RCS: An in vitro study. *Saudi J Oral Sci*. 2022;9(3):175-179.
29. Day PF, Flores MT, O'Connell AC, Abbott PV, Tsilingaridis G, Fouad AF, et al. International Association of Dental Traumatology guidelines for the management of traumatic dental injuries: 3. Injuries in the primary dentition. *Dent Traumatol*. 2020;36(4):343-359.
30. Pandolfo MT, Rover G, Bortoluzzi EA, Teixeira CS, Rossetto HL, Fernandes PCSV, et al. Fracture resistance of simulated immature teeth reinforced with different mineral aggregate-based materials. *Braz Dent J*. 2021;32(3):21-31.

Declarations

Authorship & CRediT Statement

Emine Şimşek: Conceptualization, Methodology, Funding acquisition, Project administration, Supervision, Visualization, Writing – review & editing, Writing – original draft, Data curation, Resources, Investigation, Formal analysis, Validation, Software. Sude Gül Özdemir: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Funding acquisition, Project administration. Selimcan Satar: Conceptualization, Methodology, Writing – original draft, Data curation, Resources, Investigation, Formal analysis, Validation, Software, Project administration, Funding acquisition. Fatma Selenay Uçaş Yıldız: Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Data curation. Özge Kurt: Conceptualization, Writing – review & editing, Writing – original draft, Data curation, Formal analysis, Validation, Methodology, Project administration, Supervision. Makbule Bilge Akbulut: Conceptualization, Visualization, Writing – review & editing, Supervision, Data curation, Resources, Writing – original draft, Formal analysis, Validation, Software, Methodology.

Conflict of Interest

All authors declare no conflicts of interest.

Ethics Approval & Consent

Approved by Mersin University Clinical Research Ethics Committee (ID: 2026/08, 2026-01-07, Türkiye).
Consent: na.

Data Availability

Available from the corresponding author on reasonable request.

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