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ORIGINAL ARTICLE

Effect of different restorative approaches and broken instrument removal techniques on the fracture resistance of root canal-treated teeth: an in vitro study

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Abstract

This study aimed to evaluate the effect of three different restorations—a prefabricated glass-fiber post and zirconia crown (PGF/Zc), a polyethylene woven-fiber post and zirconia crown (PWF/Zc), or a zirconia endocrown (ZE)—on the fracture resistance of teeth after broken file removal using either an ultrasonic or a micro-retrieve and repair (MR&R) system. Ninety mandibular premolar root canals were instrumented. Endodontic rotary files were intentionally fractured in the middle third of 80 teeth. Ten teeth served as a positive-control group. The broken fragments were removed from the 80 teeth and divided into two main groups: ultrasonic and MR&R. The removal times and the amount of dentin loss were measured. Following removal and single-cone obturation, the teeth were divided into four subgroups (n = 10 per group): PGF/Zc, PWF/Zc, ZE, and a negative control. All zirconia restorations were cemented with a dual-curing cement. Fracture resistance was measured using a universal testing machine with force applied at a 45° angle. Statistical analysis used the non-parametric Kruskal–Wallis test with ($\alpha = 5\%$). No significant differences were observed between the two removal methods for file removal time or weight loss ($p > 0.05$). The fracture resistance was numerically higher in the ultrasonic group; however, this difference was not statistically significant compared to the MR&R group ($p = 0.317$). Among the restored groups, ZE restorations consistently provided higher fracture resistance than PGF/Zc or PWF/Zc restorations ($p = 0.035$). Notably, PGF/Zc exhibited the lowest resistance in MR&R-treated samples. The zirconia endocrown (ZE) was the structurally superior restorative choice across all groups following fractured instrument removal.

Keywords Dental restoration · Endodontics · Endocrown · Fracture resistance · Ultrasonic

Introduction

Endodontic instrument fracture is a significant complication that can occur during all standard endodontic treatments. This can lead to future treatment failure, as it prevents the root canal system from being completely cleaned, shaped, and obturated [1]. Due to the rapid development of new technologies, numerous devices and techniques have been developed to manage broken endodontic instruments [2].

Ultrasonics has long been considered the gold standard for non-surgical removal of broken files, demonstrating high effectiveness both in vitro and in vivo [3]. However, this method has limitations; it often requires the removal of a significant amount of dentin to create a staging platform, which can compromise the root's structural integrity. Trephine burs represent another established method for removing broken files. For years, systems like the Masserann kit have been used, consisting of hollow trephine burs with diameters ranging from 1.1 to 2.4 mm [4]. While effective, the large diameter of these burs necessitates extensive dentin removal, significantly weakening the tooth structure. These disadvantages have led to the development of alternative methods.

The recently developed Micro-Retrieve & Repair (MR&R) System (Superline NIC Dental, Shenzhen, China) was designed to address these drawbacks. This system offers

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a less invasive approach, utilizing trephine burs with smaller diameters (0.7–1.2 mm) and thinner walls (0.15 mm) [4]. The primary advantages of the MR&R system are its ability to preserve more dentin and its precise engagement with the fractured instrument. Its main indications include removing broken files in the middle or apical third of straight or slightly curved root canals, where excessive dentin removal is a concern. While it offers a more conservative option, its use requires a steep learning curve and may not be suitable for all cases, particularly those with complex anatomy.

Broken instrument removal often results in the formation of ledges and loss of tooth tissue, which can lead to potential stress concentration points and cause the tooth to become physically weak [5]. Therefore, the use of appropriate canal filling systems and restorations is critical for restoring teeth with significant material loss [6].

Traditionally, dental posts have been used to retain the coronal restoration in teeth with significant loss of coronal tooth structure [6]. The clinical longevity of posts has been reported to be 11.8 years for cast metal post-and-cores, 10.2 years for prefabricated metal posts, and 12 years for fiber-reinforced composite resin posts [7]. While posts are used to provide retention, it is important to note that post preparation and placement can contribute to root weakening, rather than reinforcing the root structure. Gbadebo et al. [8] investigated the success of restoring endodontically treated teeth with glass-fiber posts. They concluded that these posts performed well in terms of post-core-crown and root fracture at 6 months. On the other hand, polyethylene fiber posts have also been introduced and are noted for their excellent biocompatibility, esthetics, and ease of use. These posts are designed to reinforce the root canal and increase fracture resistance. Their malleability allows them to be shaped without requiring additional tooth tissue removal [9].

Another alternative restoration technique that has recently gained popularity is endocrowns. According to the review article by Mannocci et al. [10], an endocrown is a monoblock restoration designed for endodontically treated posterior teeth, where the restoration's support is provided by the pulp chamber walls and the cavity margins.

Endocrowns are particularly indicated for mutilated posterior teeth with significant coronal and subgingival defects, such as short clinical crowns, shallow pulp chambers, or compromised root canal dentin. The main advantage of this approach is its minimally invasive nature. Unlike traditional post-and-core systems, endocrowns eliminate the need for space preparation within the root canal, preserving valuable radicular dentin and avoiding the risk of root perforation. This conserves tooth structure and reduces the time and complexity of the clinical procedure [2].

Furthermore, endocrowns are biomechanically advantageous. The monoblock design and adhesive cementation provide a strong bond between the remaining tooth structure. This transfers masticatory forces to the pulp chamber floor, dispersing them more favorably than post-and-core systems, which can concentrate stress in the root canal and potentially lead to root fracture. Enlarging the pulp chamber cavity and adhesive bonding increases the retention area, allowing for improved stability. An in vitro experiment evaluated the relative fracture resistance of endocrown restorations versus glass-fiber post restorations, revealing that endocrown restorations exhibit greater fracture resistance [11].

Numerous studies have investigated various restorative techniques for strengthening root canal-treated teeth. However, the effects of these restorations on the fracture resistance of roots following the removal of broken files remain inadequately studied. The purpose of this study was to evaluate how three different restorations—a prefabricated glass-fiber post and zirconia crown (PGF/Zc), a polyethylene woven fiber and zirconia crown (PWF/Zc), or a zirconia endocrown (ZE)—affect the fracture resistance of teeth after broken file removal using either an ultrasonic or a Micro-Retrieve & Repair (MR&R) technique.

The null hypotheses of this study were as follows:

1. There would be no difference between the ultrasonic and MR&R systems regarding the removal times of fractured files or the amount of tooth tissue removed.
2. The techniques used for removing broken files and the subsequent prosthetic restorations would not affect tooth fracture resistance

Materials and methods

Sample size analysis

The required sample size was determined using G*Power 3.1.9.4 software, aiming for 85% statistical power and a significance level of 5%. A sample size of nine molars per group was estimated to yield an effect size of 0.5. The sample size was increased by 11.1% to ten molars per group, providing 90 samples to compensate for any pretest misses.

Tooth selection and preparation of specimens

The study protocol was approved by the Ethics Committee of the Faculty of Dentistry, X University, for Non-Pharmaceutical and Non-Medical Product Research (Decision No. 2020/05). The teeth used in this research consisted of 90 human mandibular premolars, which had been extracted from patients for clinical reasons (e.g., orthodontic or periodontal) unrelated to the present study. Written informed consent was obtained for the use of these teeth for research purposes. The selection criteria included a single, straight, round root canal and a buccolingual-to-mesiodistal diameter

ratio of less than 1.5 at the apical 5 mm level. Teeth with root canal curvature greater than 5 degrees were excluded to ensure standardization. The internal anatomy of the root canals was evaluated using periapical radiography to confirm a single canal configuration with no splits or significant anatomical variations that could affect load-bearing capacity.

Additionally, teeth with pre-existing restorations, root cracks, root resorption, or prior endodontic treatment were not included. Immediately following extraction, the teeth were cleaned with a periodontal scaler to remove soft- and hard-tissue residues and subsequently disinfected by immersion in a 5.25% sodium hypochlorite solution for 10 min. Following this disinfection protocol, the teeth were stored in a refrigerator at 4 °C in distilled water at 100% humidity until use, with a maximum storage time of 1 month. Any teeth that did not meet the initial selection criteria after cleaning, as well as those identified with anatomical variations such as two root canals during access cavity preparation under magnification, were excluded and replaced with new samples that fulfilled all standardization requirements.

The crowns of the teeth were sectioned 2 mm coronal to the cemento-enamel junction using a low-speed diamond saw with water coolant to standardize the root length at 14 ± 1 mm. All teeth were then shaped using the ProTaper Universal (PTU) nickel–titanium file system (Dentsply, Tulsa Dental, Oklahoma, USA) via an endodontic handpiece (X-Smart Plus; Dentsply, Tulsa Dental, Oklahoma, USA), following the manufacturer's instructions. The files used were S1 (size 17, 0.02 taper), S2 (size 20, 0.04 taper), and F1 (size 20, 0.06 taper). Following each instrument change, the root canals were irrigated 1 mm from the apex with 2 ml of 5% sodium hypochlorite using a 30-gauge needle (Microvem, Sakarya, Turkey).

A 23.8 mm × 0.6 mm carbon separating disk was used to notch the 4-mm portion of the PTU F2 (size 25, 0.08 taper) file that would be broken in the canal, except for group C (positive control). The PTU F2 file, which has a convex, triangular cross-section, was then operated in the middle third of the root at 300 rpm and a torque of 2.5 Ncm. The process was repeated until the notched file fractured. All instruments were pre-notched and successfully fractured at the notch region to ensure a standardized fragment length and location. No instances of unpredictable torsional fatigue fracture were included. The broken fragments were then randomly divided into two main groups (Group A and Group B).

Group A ($n = 40$): In this group, the ultrasonic method was used to remove broken fragments from the root canals. A straight access path and staging platform were created with a modified Gates-Glidden #3 bur (Lexicon GG Burs, Tulsa Dental, Oklahoma, USA) as described by Ruddle (2004). Using an LED ultrasonic device (D600 DTE; Woodpecker, Guilin, China) and fine tips (ED6-ED15 DTE; Woodpecker, Guilin, China) on a low power setting, a trough was meticulously created around the coronal portion of the broken instrument. The tips were used under magnification with regular counterclockwise movements and no water cooling to avoid contact with the fragment. The canal was irrigated with saline water and dried with a paper point at 30-s intervals. Parallel periapical radiographs verified removal success.

Group B ($n = 40$): The broken fragments were removed from the root canals using the MR&R system as directed by the manufacturer. The coronal enlargement was created by successively running #60/0.04, #70/0.03, and #80/0.02 NiTi files over the broken instrument's coronal tip. Using a #90/0.01 NiTi file, a staging platform was built over the broken instrument piece. After establishing the staging platform, a trephine bur (outer diameter: 0.9 mm; inner diameter: 0.6 mm) was used with a 500-rpm endodontic motor (Dentsply Maillefer, Ballaigues, Switzerland) in a counterclockwise direction to expose 1–1.5 mm of the broken file. A microtube was used to grasp and extract the fragment. The canal was irrigated with saline water and dried with a paper point at 30-s intervals. Parallel periapical radiographs verified removal success.

For both experimental groups (Groups A and B), the same operator (B.A.B.) who conducted the root canal procedure in all groups removed the broken file from the root canal using an EyeMag Pro F 3.5 × loupe (Carl Zeiss, Oberkochen, Germany). Prior to and following file retrieval, all teeth were examined under a stereo microscope (10x) to check for any evidence of cracks or fractures.

Group C ($n = 10$): For the positive-control group, ten teeth were shaped using S1, S2, and F1, F2, and F3 (size 30, 0.09 taper) files of the PTU with an endodontic handpiece (X-Smart Plus; Dentsply, Tulsa Dental, Oklahoma, USA) without any broken fragments as described above. Following each instrument change, the root canals were irrigated 1 mm from the apex with 2 ml of 5% sodium hypochlorite using a 30-gauge needle (Microvem, Sakarya, Turkey).

A maximum duration of 45 min was allocated for each attempt to remove a file. Samples in which the instrument could not be retrieved within this limit were considered unsuccessful and were replaced with new samples to ensure the required number of specimens for the subsequent mechanical testing phase. After removing broken files, all root canals were standardized by shaping with a ProTaper Universal (PTU) F3 file using an endodontic handpiece. All canals were then irrigated with 5 mL of 17% EDTA (Canal-Pro; Coltene-Whaledent) solution for 1 min to remove the smear layer, followed by a final rinse with 5 mL of saline. The root canals were dried with ProTaper F3 paper points (Dentsply, Maillefer, Ballaigues, Switzerland). To quantify the amount of tooth structure removed, the weight loss of each tooth was measured with a microbalance (PS 510.R1; Radwag, Radom, Poland) before and after retrieval. The time

required for each removal procedure was recorded with a digital chronometer.

Except for the negative control groups (Groups A4 and B4), a single-cone obturation technique was used for root canal obturation, which involved a master cone (F3 gutta-percha, Maillefer-Dentsply) and sealer (AH Plus; Dentsply, Tulsa Dental, Oklahoma, USA). After obturation, the excess gutta-percha was cut at the pulp chamber level and cleaned with a cotton pellet and alcohol. All teeth were then stored in a 100% humidity environment at 37◦°C for 7 days to ensure complete setting of the sealer. Following that, they were distributed randomly into four subgroups, except for Group C (which utilized Coltosol, a temporary filling from Coltene/Whaledent, Switzerland, for access cavity sealing), based on the chosen restoration approach (Table 1): prefabricated glass-fiber post and zirconia crown (PGF/Zc), polyethylene woven-fiber post and zirconia crown (PWF/Zc), zirconia endocrown (ZE), and no restoration was used in the negative control groups. The materials used in restorations, along with their compositions, are listed in Table 2.

Table 1 Classification of the study groups

Group	Removing procedure	Restoration technique
Group A	Ultrasonic	Group A1 PGF/Zc ($n=10$)
		Group A2 PWF/Zc ($n=10$)
		Group A3 ZE ($n=10$)
		Group A4–Negative Control (no root canal filling and restoration) ($n=10$)
Group B	MR&R	Group B1 PGF/Zc ($n=10$)
		Group B2 PWF/Zc ($n=10$)
		Group B3 ZE ($n=10$)
		Group B4–Negative Control (no root canal filling and restoration) ($n=10$)
Group C (positive control)	No broken fragment	Only root canal filling ($n=10$)

PGF/Zc, prefabricated glass-fiber post and zirconia crown; PWF/Zc, polyethylene-woven fiber and zirconia crown; ZE, zirconia endocrown

Prefabricated glass-fiber post with zirconia crown group (PGF/Zc)

A glass-fiber post (Reforpost; Angelus, Londrina, PR, Brazil) with a round cross-section was restored to two subgroups (Groups A1 and B1). The system's own drill with a working length of 7 mm was used to prepare the post space. The post was then confirmed to be fully fitted in the canal. The prefabricated glass fiber (no. 2 Reforpost; Angelus, Londrina, PR, Brazil) post was cut to the desired length with a diamond disk, leaving an excess of 3 mm to retain the core. The posts were cleaned with alcohol and air-dried for 60 s before applying the luting agent Monobond N (Ivoclar

Table 2 The materials used in restorations and their compositions

Material	Manufacturer	Composition	Lot
Monobond N	Ivoclar Vivadent AG, Schaan, Liechtenstein	MDP, 3-trimethoxysilylpropyl methacrylate, ethanol, disulfde acrylate	V43819
Multilink N	Ivoclar Vivadent AG, Schaan, Liechtenstein	HEMA, dimethacrylate, barium glass, yttrium trifluoride, spheroid-mixed oxide	Y26001
Reforpost	Angelus, Londrina, PR, Brazil	Glass fiber 80%, pigmented resin (Bis-GMA) 19%, and stainless steel filament 1%	101,491
Ribbond	Ribbond, Seattle, WA, USA	Ultra-high molecular weight polyethylene, Homopolymer H-(CH_2-CH_2)n–H	D758T0
G-aenial Universal Flow	GC, Tokyo, Japan	Matrix: UDMA, Bis-MEPP, TEGDMA, pigment-photo-initiatorFiller: Silicon dioxideStrontium glass	1,012,021
Clearfil DC Core Automix One	Kuraray Noritake Dental, Okayama, Japan	Paste A: hydrophobic ARDM, hydrophobic ALDM, Bis-GMA, hydrophilic ALDM, dl-CQ, filler, pigments, initiators Paste B: hydrophilic ALDM, hydrophobic ARDM, TEGDMA, accelerators, filler	370,283
VITA YZ T	VITA Zahnfabrik, Bad Säckinger, Germany	Zirconium oxide 90.9–94.5%, hafnium oxide 1.5–2.5%, yttrium oxide 4.0–6.0%, aluminum oxide 0.0–0.3%, iron oxide 0.0–0.3%	63,320

CQ, camphorquinone (photo-initiator); Bis-GMA, bisphenol A-glycidyl dimethacrylate; HEMA, 2-hydroxyethyl methacrylate; ARDM, aromatic dimethacrylate; ALDM, aliphatic dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; MDP, 10 10-methacryloyloxydecyl dihydrogen phosphate; UDMA; urethane dimethacrylate; Bis-MEPP, ethoxylate dimethacrylate

Vivadent AG, Schaan, Liechtenstein), as recommended by the manufacturer. The posts were then cemented into the tooth using Multilink N (Ivoclar Vivadent AG, Schaan, Liechtenstein), a dual-curing self-adhesive luting agent, as directed by the manufacturer. The luting agent was placed in the root canals with an elongation tip. Next, the posts were covered with resin cement and gently pressed into the prepared root canals using finger pressure. After removing the excess luting agent, the occlusal surface was polymerized for 40 s with an LED curing unit (Elipar S10; 3 M ESPE; St. Paul, Minnesota) at an intensity of 1,200 mW/cm^2. The light tip was placed close to the surface to ensure maximum light output.

Polyethylene woven fiber post with zirconia crown group (PWF/Zc)

The prefabricated glass-fiber post system's own drill with a working length of 7 mm was used to prepare the post space in two subgroups (Groups A2 and B2). The custom-made polyethylene-woven fiber (Ribbond) was cut to a length exceeding twice the distance between posts using specialized scissors made of hardened stainless steel blades. This ensured that 3 mm of the post remained above the root canal, allowing for proper retention of the composite core. The bonding agent (Monobond N) was applied to the polyethylene-woven fiber (Ribbond). For cementation, Multilink N (Ivoclar Vivadent AG, Schaan, Liechtenstein) was used as a dual-curing luting agent, and the resin cement was placed in the canal using an elongation tip. The polyethylene woven fiber was shaped into a "V" and inserted into the canal, with the excess "ear" removed. The fiber was tightly inserted into the canal space using an endodontic plug. After waiting 5 min for the setting time, the occlusal surface was polymerized as described in the PGF/Zc group.

Core build-up

To standardize the coronal portion, the crown portion was fabricated in prefabricated glass-fiber post and polyethylene-woven fiber post groups (Groups A1, A2, B1, and B2) using the mandibular premolar mold's prefabricated core buildups (Parapost Paraform No. #5, Coltene Whaledent). The core build-up was accomplished using a dual-cure core material (Clearfil DC Core Automix One). The excess material was immediately removed from the cavosurface margins. Then, the occlusal surface was light-cured for 40 s using a light-emitting diode (LED) curing unit (Elipar S10; 3 M ESPE; St. Paul, Minnesota) with a 1,200 mW/cm^2 light intensity. The curing tip was held at a constant distance of 2 mm from the restoration (Fig. 1).

Zirconia endocrown (ZE)

Following root canal fillings, the floor of the pulp chamber was covered with a flowable composite (G-aenial Universal Flo) to achieve a thickness of 1 mm in the central retention cavity in two subgroups (Groups A3 and B3). The pulp chamber floor was flat, and the central retention cavity was 4 mm deep. The axial walls were aligned with a conical diamond drill held perpendicular to the base of the pulp, and an internal wall angle of 8–10° was obtained. The cavity's floor

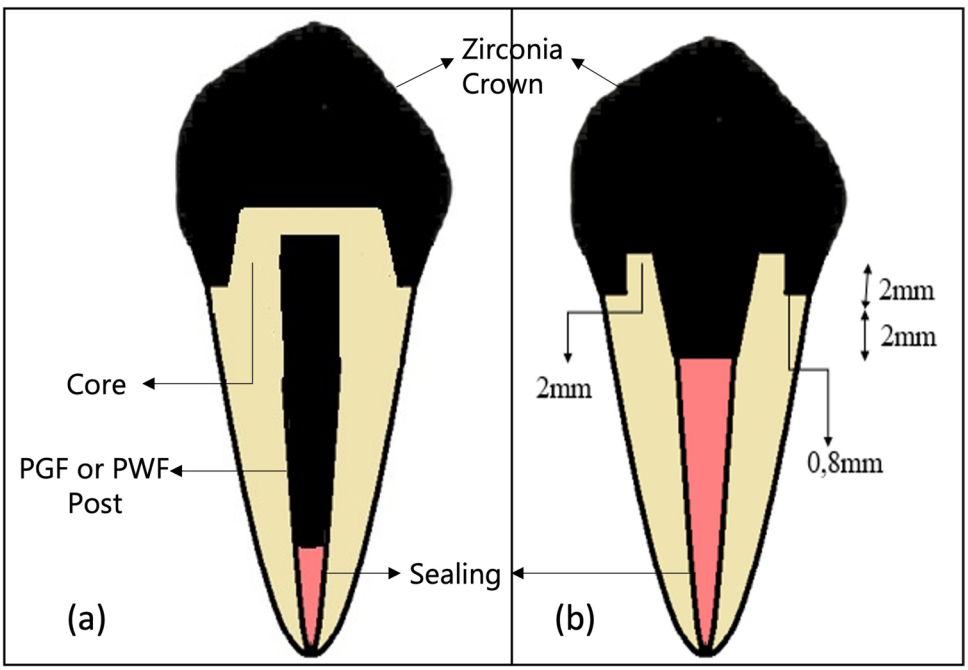

Fig. 1 Schematic representation of the preparation of teeth. **a** Prefabricated glass fiber (PGF)/Polyethylene woven-fiber (PWF) post and zirconia crown (Zc). **b** Zirconia endocrown (ZE)

angles were set at 90° ± 4°, and the transitions between the walls were also set at 90°. The tooth walls were made with a width of 0.8 mm and a shoulder finish line of 6°. Rounding the sharp corners completed the preparation (Fig. 1).

The prepared teeth were scanned and digitized using a model scanning device (Dental Wings, Montreal, Canada), and the endocrowns were designed using DWOS software. The endocrowns were milled from monolithic zirconia blocks (VITA YZ T) with a diameter of 98.4 mm and a height of 18 mm. We used a five-axis CAM device (Yenamak D50, Yenadent, Istanbul, Turkey) and zirconia burs measuring 1 mm and 2 mm in diameter. The occlusal thicknesses were checked for consistency. All restoration crown lengths were adjusted to a standard of 7 mm (Figs. 2 and 3).

Cementation

The inner surfaces of the zirconia restorations were abraded using airborne-particle technology with 50 µm aluminum oxide (Al_2O_3) particles at a pressure of 2.5 bar for 15 s to create a roughened surface. The restorations were then thoroughly cleaned with a water spray for 30 s and ultrasonically cleaned in 96% ethanol for 10 min to remove residual particles. The restorations were then air-dried with an oil-free air syringe. Subsequently, a universal primer (Monobond N; Ivoclar Vivadent AG; Schaan, Liechtenstein) was applied to the bonding surfaces of the restorations using a microbrush and allowed to react for 60 s as per the manufacturer's instructions, followed by gentle air-thinning.

The restorations were then cemented to all prepared teeth using a dual-curing resin cement (Ivoclar Vivadent AG, Schaan, Liechtenstein). The cement was mixed according to the manufacturer's directions and applied to the intaglio surfaces of the restorations. The restorations were seated with firm finger pressure, and excess cement was removed with a microbrush. Then, the restorations were light-cured from all directions for 40 s using an LED curing unit (Elipar S10; 3 M ESPE; St. Paul, Minnesota).

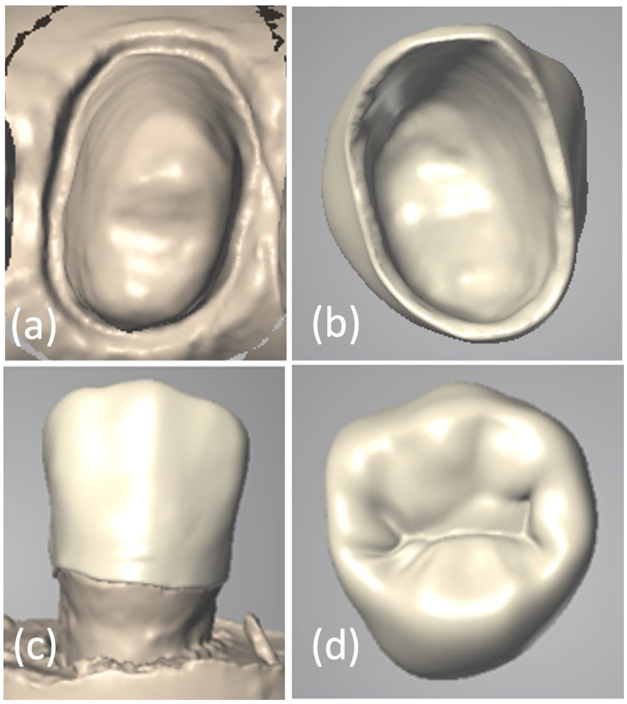

Fig. 2 Digital models of the teeth with prefabricated glass-fiber post and polyethylene woven fiber post core were scanned with a model scanning device (Dental Wings, Montreal, Canada). **a** Occlusal view of prepared premolar tooth after post–core application. **b** Inner view of the crown. **c** Buccal view of the crown. (d) Occlusal view of the crown

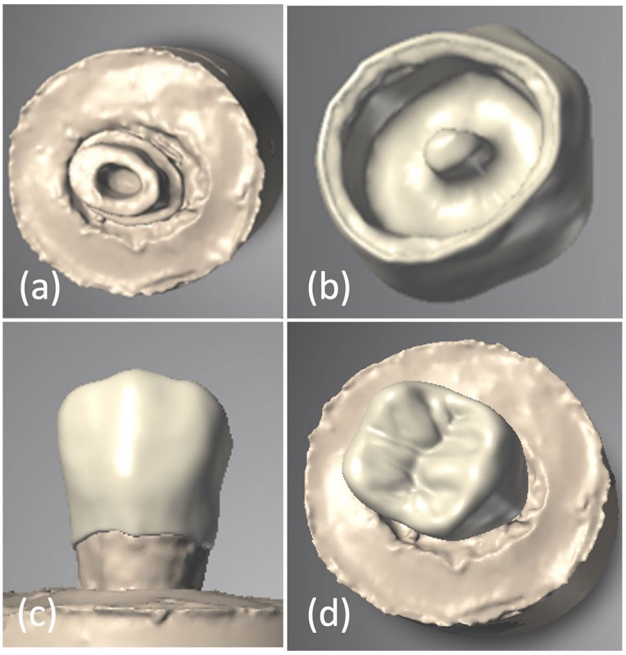

Fig. 3 Digital models of the prepared single-rooted premolar teeth for endocrown were scanned with a model scanning device (Dental Wings, Montreal, Canada). **a** Occlusal view of prepared premolar teeth. **b** Inner view of the endocrown. **c** Buccal view of the endocrown. **d** Occlusal view of the endocrown

Fracture resistance test

To model the periodontium, the roots of all groups were coated with 0.2–0.3 mm-thick polyvinyl siloxane-containing second impression material (Oranwash L, Zhermack, Italy). The teeth were then vertically embedded in self-curing acrylic cold resin (Imicryl, Konya, Turkey) in 20 mm plastic molds, exposing the coronal 2 mm of the cemento-enamel junction (CEJ).

A static fracture resistance test was conducted using a universal testing machine (Besmak, Ankara, Turkey) to determine the force required to fracture the samples. Each sample was securely mounted on the machine's lower arm using a customized clamping device that ensured the restoration's buccal surface faced the loading tip at a 45° angle. The test was conducted using a spherical steel tip with a 5 mm diameter, which was brought into contact with the buccal surface of the restorations at a crosshead speed of 1 mm/min. The applied force was continuously monitored and recorded in Newtons (N) using the machine's load cell, with the peak force at the time of fracture being registered as the fracture resistance. An abrupt drop in the force–displacement curve indicated the moment of fracture.

Following the fracture test, all samples were analyzed for fracture type using a stereomicroscope (SZTP; Olympus Optical Co., Ltd., Tokyo, Japan; 10 × magnification). Two examiners (B.A.B. and D.B.) classified the fracture modes, and they were blinded to the experimental groups to ensure an unbiased assessment. Fractures were classified as either non-catastrophic (repairable), confined to the coronal portion above the cemento-enamel junction (CEJ), or catastrophic, if the fracture line propagated to the root below the CEJ. Representative photographs of each failure mode were captured using a digital camera attached to the microscope (Fig. 4).

Statistical analysis

The Shapiro–Wilk test was used to check if the data from removal times, weight loss of all samples, and fracture resistance values followed a normal distribution. In contrast, Levene's test assessed the equality of variances. The results indicated that the data did not follow a normal distribution. Consequently, the non-parametric Kruskal–Wallis test was employed for group comparisons, and the Mann–Whitney U test was used for post-hoc analysis. The data analysis was performed using SPSS 22.0 software (IBM SPSS, Chicago, IL, USA), with a significance level set at $p < 0.05$ and a 95% confidence interval.

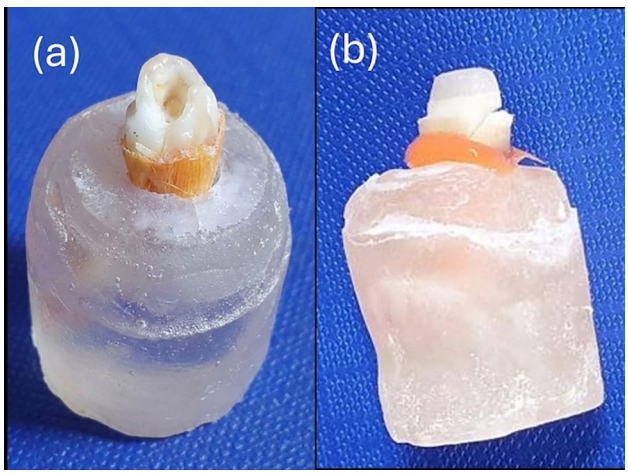

Fig. 4 Representative digital microscope images illustrating the classification of failure modes: **a** Non-catastrophic (repairable) fracture, confined to the coronal portion above the cemento-enamel junction (CEJ). **b** Catastrophic (non-repairable) fracture, where the fracture line propagated below the CEJ into the root structure

Results

In terms of file removal times, there was no statistically significant difference between the methods used ($p > 0.05$). However, it was found that the average removal times for broken files using the MR&R method were longer (Table 3).

Regarding the weights removed from the teeth, there was no significant difference between the methods used ($p > 0.05$). However, the ultrasonic method resulted in a greater mean weight loss for the teeth. Notably, two of the 40 samples took longer than 45 min to remove in the ultrasonic group, resulting in a 95% success rate in removing broken files. In contrast, the MR&R group achieved a success rate of 90%.

The fracture resistance (in Newtons) values for all groups are presented in Table 4. Overall, the fracture resistance of teeth treated with the ultrasonic method was higher than that of those treated with the MR&R method, although this difference was not statistically significant (p = 0.317).

Significant differences in fracture resistance were detected between the restoration and control groups. Specifically, the PGF/Zc group showed a significant difference (p = 0.035), whereas the PWF/Zc (p = 0.529) and ZE (p = 0.28) groups did not. A significant difference was also found between the negative control groups (p = 0.043). In contrast, no significant difference was observed between the restored groups (Groups A1, A2, A3, B1, B2, or B3) and the positive-control group (p > 0.05) (Fig. 5).

Within the ultrasonic group, the highest fracture resistance was found in the ZE subgroup. However, no significant differences were observed among the ZE, PGF/Zc, and PWF/Zc groups (p > 0.05). Conversely, the negative control

Table 3 Comparison of retrieval time and dentin weight loss during the removal of separated instruments using ultrasonic and MR&R systems (Mean ± Standard Deviation)

	Ultrasonic	MR&R	*p*
Removal time (second)	627,83 ± 482,19	806,95 ± 518,44	0.059
Weight loss (gram)	0,23 ± 0,07	0,20 ± 0,09	0.098

Mann–Whitney U-test *p* value > 0.05

Table 4 Statistical comparison of fracture resistance (N) of the ultrasonic and MR&R system and different restoration techniques

	Ultrasonic	MR&R	*p*
PGF/Zc	$1214{,}06 \pm 371{,}40^{Ab}$	$894{,}98 \pm 247{,}57^{Bb}$	0.035*
PWF/Zc	$1368{,}34 \pm 478{,}19^{Ab}$	$1216{,}78 \pm 459{,}21^{Ac}$	0.479
ZE	$1518{,}39 \pm 307{,}69^{Ac}$	$1381{,}41 \pm 260{,}58^{Ac}$	0.297
Negative control	$284{,}99 \pm 74{,}67^{Aa}$	$214{,}46 \pm 68{,}45^{Ba}$	0.021*
Positive control	$1185{,}7 \pm 461{,}58^{bc}$	$1185{,}7 \pm 461{,}58^{bc}$	
p	0.001*	0.001*	

PGF/Zc, prefabricated glass-fiber post and zirconia crown; PWF/Zc, polyethylene woven fiber and zirconia crown; ZE, zirconia endocrown

Methods of removal are denoted by capital letters. Lowercase letters denote filling techniques used in conjunction with the same removing technique. There is a difference between different letters

An asterisk (*) indicates a statistically significant difference between groups ($p < 0.05$)

subgroup exhibited the lowest fracture resistance, which was significantly different from that of the other subgroups (p = 0.001).

Similarly, within the MR&R group, the highest fracture resistance was found in the ZE subgroup. While the ZE and PWF/Zc groups showed no significant difference (p = 0.481), a significant difference was observed between the PGF/Zc and ZE groups (p = 0.001). No significant difference existed between the PWF/Zc and PGF/Zc groups (p = 0.105). Consistent with the ultrasonic group, the MR&R negative control subgroup presented the lowest fracture resistance, with a significant difference from the other subgroups (p = 0.001).

The distribution of fracture types is summarized in Table 5. The vast majority of samples exhibited catastrophic fractures. Only two endocrown (ZE) subgroup samples demonstrated a non-catastrophic, repairable fracture type. Due to the very low incidence of this event, a statistical analysis of fracture type could not be performed.

Discussion

Endodontic instrument fractures during intracanal shaping pose challenges for clinicians and patients alike, potentially leading to root canal treatment failure and increased anxiety [12]. The literature contains numerous studies evaluating methods for removing broken instruments from root canals. These investigations focus on the success rates of various techniques [13], the duration of removal procedures [14], and material loss during the process [4, 15]. The primary aim of this in vitro study was to evaluate the immediate biomechanical consequences of two broken file retrieval techniques (ultrasonic and MR&R system) and subsequent restoration types (PGF/Zc, PWF/Zc, and ZE) on the fracture resistance of mandibular premolars. Our findings offer

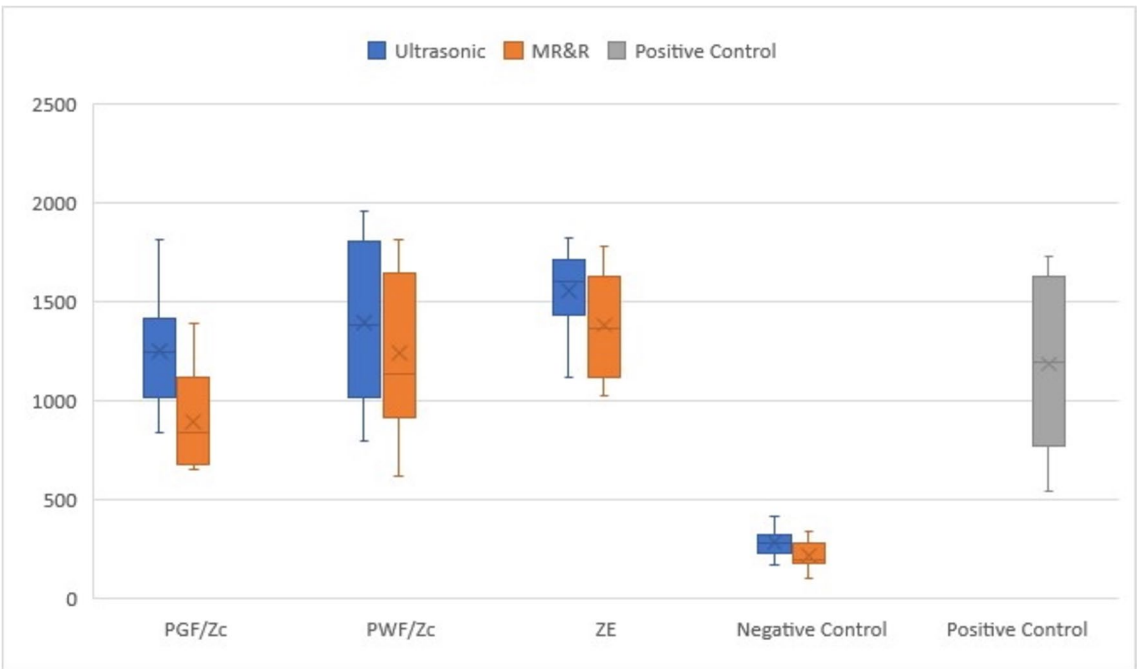

Fig. 5 Fracture resistance (N) of teeth after broken file removal using ultrasonic or MR&R systems, followed by restoration with different techniques. PGF/Zc, prefabricated glass-fiber post and zirconia crown; PWF/Zc, polyethylene-woven fiber and zirconia crown; ZE, zirconia endocrown

Table 5 Evaluation of fracture types in terms of restorability

	Ultrasonic		MR&R	
	Non-catastrophic fracture	Catastrophic fracture	Non-catastrophic fracture	Catastrophic fracture
PGF/Zc	0	10	0	10
PWF/Zc	0	10	0	10
ZE	0	10	2	8
Negative control	0	10	0	10
Positive control	*0*	-	-	*10*
Total	0	50	2	48

PGF/Zc, prefabricated glass-fiber post and zirconia crown; PWF/Zc, polyethylene woven fiber and zirconia crown; ZE, zirconia endocrown,

critical insights into managing compromised root structures, particularly regarding the trade-offs between dentin preservation and structural integrity. Initial analysis indicated that although the MR&R system led to slightly less weight loss than the ultrasonic technique, the difference in dentin loss was not statistically significant. This finding led to the acceptance of our first null hypothesis, which contrasts with the previous reports suggesting greater dentin removal with ultrasonic tips [4]. This disparity may be attributed to the specific selection of teeth (mandibular premolars) in the present study.

Mandibular premolars were selected, because they are a prevalent site for endodontic treatment failure and possess distinct anatomical features. As Madarati et al. [15] noted, they typically present with a single canal, simplifying standardized preparation and subsequent file retrieval. This in vitro study employed an irrigation protocol to adhere to standard principles of endodontic disinfection. Furthermore, the single-cone obturation technique was chosen to ensure predictable and uniform sealing, thereby minimizing variability compared to lateral compaction, as previously demonstrated [16].

Similarly, the average removal times for the ultrasonic (10.45 ± 8.03 min) and MR&R (13.44 ± 8.64 min) groups were not significantly different. This challenges the notion of a time advantage for either system, a parameter noted for its wide variability in the literature [17, 18]. Researchers have reported widely varying estimates for the duration required to remove a broken instrument; for instance, Yang et al. [4] estimated 45 min, Suter et al. [17] suggested a range of 45–90 min, and Terauchi et al. [2] reported times ranging from 3 to > 60 min. While a separate study utilizing the MR&R system reported a mean removal time of 8.55 ± 5.81 min for broken files in the apical position of mandibular incisors [19], our specific results—10.45 ± 8.03 min for the ultrasonic group and 13.44 ± 8.64 min for the MR&R group—found no significant difference between the two techniques.

Studies directly comparing the MR&R and ultrasonic techniques for removing broken instruments are scarce in the literature. However, a study by Yang et al. [4] compared various microtube systems and found that the MR&R system and its modified version were more successful than other microtube techniques. The MR&R system and the modified MR&R system were found to be more successful than other microtube techniques. Consequently, we selected the MR&R system for removing broken files in our study. In contrast, Yang et al. [4] completely removed broken instruments using the MR&R system. Our study, however, encountered a 90% success rate in the MR&R group. This difference could be attributed to variations in tooth selection and methodological differences. In vitro investigations by Souter et al. [5] using ultrasonic tips reported 100% and 73.3% success rates for the middle and apical thirds, respectively. Similarly, Cujé et al. [20] achieved 100% success in the middle third of the regions. Overall, the existing literature suggests that the ultrasonic system has a high success rate (approximately 95%) in removing broken instruments.

Researchers have highlighted critical factors related to the removal of broken instruments, particularly when dealing with endodontic files. Souter et al. [5] reported that attempting to remove a broken file significantly weakened the middle and apical thirds of the tooth. When a file breaks in the apical third, caution is advised, and removal attempts should not always be pursued. Similarly, Ward et al. [21] found that the ultrasonic technique was successful in removing broken files. However, attempting to remove files beyond the canal curvature caused extensive tooth damage. The middle part of the root canal was chosen as the fracture position for the separated file, as this region requires the most aggressive dentin removal for instrument staging, thus maximizing the opportunity to assess the biomechanical damage caused by the retrieval systems. In this in vitro study, a statistically significant difference in fracture resistance was found between the ultrasonic and MR&R negative control groups after removing the broken file from the middle third of the root canal, with teeth treated by the ultrasonic system proving more resistant. Also, this study showed no significant difference in dentin loss between the two systems. We postulate that the discrepancy is rooted in the mechanism of dentin removal. Due to its geometry, the MR&R system relies on a trephine bur, which is prone to creating ledge-like formations [18], and microcracks within the root dentin. These defects act as severe stress concentration points, initiating failure at lower force levels [5]. Conversely, the controlled, focused action of the ultrasonic tips likely facilitates a more homogeneous preparation around the staging platform, resulting in less procedural micro-damage, thereby preserving residual root integrity. This aligns with Ward et al. [21]

findings that aggressive removal attempts compromise the tooth regardless of the technique.

For the bonding procedures, a specific dual-cure cement system (Multilink N) was chosen due to its proven reliable adhesion to both dentin and zirconia, a key factor in the longevity of monobloc restorations [22]. The tested restorations (Zirconia crowns) were standardized for material, color, and translucency to eliminate the confounding effects of aesthetic material variables on light transmission and cement polymerization [23]. Finally, the static fracture test was employed, because it is a well-established protocol for comparative biomechanical analysis, providing a reproducible measure of instantaneous maximum strength [23].

Endocrown restorations are used to restore root canal-treated teeth that have experienced significant loss of coronal structure, finding application across various dentitions, including incisors, premolars, and molars [18, 24–26]. In their systematic review and meta-analysis, Sedrez-Porto et al. [27] concluded that endocrowns exhibited clinical survival rates comparable to intraradicular post restorations in molars.

The monobloc structure of endocrowns inherently withstands greater stress than conventional post-core systems with multiple interfaces [28]. Furthermore, Forberger et al. [29] demonstrated that endocrowns possess comparable fracture resistance to zirconia, gold, or glass-fiber posts, with some studies even reporting statistically significantly higher resistance than glass fiber posts [11, 30]. In the current investigation, teeth restored with ZE (Endocrowns) exhibited superior fracture resistance compared to those restored with PGF/Zc and PWF/Zc systems. This difference was particularly notable in teeth with compromised roots following the removal of broken files using the MR&R system. Consistent with previous biomechanical studies [28, 29], endocrown restorations (ZE) consistently provided the highest fracture resistance across all retrieval groups. These findings led to the rejection of our second null hypothesis. This biomechanical advantage is attributed to the endocrown's monobloc design, which minimizes material interfaces and reduces the stress concentration points inherent in conventional post-core-crown systems [28]. By leveraging the strength of the entire remaining coronal dentin, endocrowns represent a structurally superior choice for teeth weakened by endodontic procedures, including file retrieval. Our results reinforce the conclusion by Sedrez-Porto et al. [27] regarding the clinical viability of endocrowns.

It is posited that the elastic modulus of the polyethylene woven fiber (PWF) closely simulates that of dentin [31], which is thought to promote appropriate stress distribution along the root, effectively enabling the dentin and post-core to function as a single unit. Despite this theoretical advantage, studies focusing on PWF posts remain limited [31]. Previous literature offers mixed results; one study found PWF posts more resistant than cast posts but less resistant than glass-fiber posts. Additionally, Sirimai et al. [32] found that while PWF post alone did not significantly increase strength, the resulting fractures were often more repairable. Conversely, Torabi and Fattahi [33] found no significant difference in fracture strength or catastrophic fracture formation between the PWF post and prefabricated glass-fiber post groups in lower premolars.

The Polyethylene Woven Fiber Post (PWF/Zc) system demonstrated a noteworthy interaction with the MR&R retrieval method. In the MR&R-treated groups, the PWF/Zc system showed no significant difference in fracture resistance compared to the superior ZE group. This suggests that the low elastic modulus of the polyethylene fiber, which closely mimics dentin [31], may offer an ideal stress-dampening effect. This characteristic is critical in compensating for the structural compromise (microcracks) potentially induced by the MR&R trephine bur, thereby providing better stress distribution than the more rigid PGF/Zc system.

The teeth in this study that had files removed using the ultrasonic method exhibited higher fracture resistance when restored with ZE than the PGF/Zc and PWF/Zc groups. However, these differences were not statistically significant. Notably, within the MR&R group, no significant difference in fracture resistance was observed between the PWF/Zc and ZE groups. This supports the hypothesis that the PWF system may effectively distribute stress and mitigate the anatomical alterations associated with the MR&R system.

Minimizing dentin removal during the retrieval of broken instruments is paramount to ensure long-term success. The technique employed for removal is equally critical, as it impacts the subsequent choice of restoration that supports the remaining tooth structure and reduces the risk of root fracture. Fracture resistance was lower in the groups utilizing the MR&R system compared to the ultrasonic group; however, this difference was diminished when teeth were restored with ZE and PWF/Zc.

Our methodology involved transmitting force to the zirconia crown rather than directly to the core structure, a deliberate approach to better simulate clinical conditions [34]. This led to a high incidence of catastrophic (irreparable) fractures across all groups, an observation that underscores the severe biomechanical risk associated with instrument retrieval. The fact that only two endocrown samples exhibited a repairable fracture type highlights the potentially limited scope for repairable failure when a rigid crown restoration is placed on an already compromised root.

The most significant limitation of the present study is the reliance on a static fracture test, which fails to account for the cumulative damage caused by cyclic loading and thermal changes (in vivo aging), thus profoundly affecting the observed longevity of bonded restorations. A second methodological constraint relates to standardized canal

anatomy: instrument removal was performed exclusively in straight canals. However, because instrument fractures are most prevalent in curved canals, particularly in molars [35], this standardization limits the direct clinical generalization of the retrieval procedure. Furthermore, a significant gap in the literature exists; to our knowledge, no prior studies have directly compared PGF/Zc, PWF/Zc, and ZE restorations following instrument retrieval, limiting the direct comparative context of our findings. Therefore, future research should incorporate thermomechanical cycling to mimic in vivo conditions better and utilize a more biomimetic design. An extended investigation is warranted to directly compare the long-term performance and failure characteristics of PGF/Zc, PWF/Zc, and ZE restorations following instrument retrieval, employing aging protocols to enhance clinical relevance.

Conclusion

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

1. No statistically significant difference was found between the Ultrasonic and MR&R (Micro-Retrieval and Repair) systems in terms of removal time or the extent of dentin weight loss.
2. The file retrieval technique has a significant impact on the tooth's residual fracture resistance. The ultrasonic method resulted in a minor decrease in tooth strength compared to the MR&R system, particularly in unrestored teeth, suggesting that the MR&R system may induce more compromising micro-damage.
3. The choice of restorative material is critical for teeth compromised by file retrieval. Endocrown (ZE) restorations consistently provided the highest overall fracture resistance across all retrieval groups.
4. The Prefabricated Glass Fiber Post and Zirconia Crown (PGF/Zc) restorations exhibited lower fracture resistance after the MR&R procedure. As structurally superior alternatives, Endocrown (ZE) or Polyethylene-Woven-Fiber Post and Zirconia Crown (PWF/Zc) restorations are recommended for restoring roots compromised by broken file removal.

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Author contributions Büşra Avuçalmaz Baştuğ: conceptualization, methodology, investigation, software, formal analysis, data curation, and writing—original draft; Durmuş Alperen Bozkurt: validation, investigation, project administration, resources, visualization, supervision, and writing—review and editing.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval This research project was approved by the Ethics Committee of the Faculty of Dentistry of Necmettin Erbakan University for Non-Pharmaceutical and Non-Medical Product Research (Decision No. 2020/05). The patient's informed consent was obtained prior to the extraction of the teeth used in the current study. A total of 90 human mandibular premolar teeth, extracted for orthodontic or periodontal reasons, were used in this study.

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