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Investigating the Effect of PIPS Technique by Using Er,Cr:YSGG Irradiation for Sealer Removal in Endodontic Retreatment

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ABSTRACT

Objective: This study aimed to evaluate the effectiveness of the Er,Cr:YSGG 2780 nm laser pulse duration during root canal retreatment using the laser-activated irrigation method (PIPS).

Methods: The study investigated the cleanliness of root canal walls in single-rooted premolars using PIPS. Teeth were initially instrumented, filled with bioceramic (BC) sealer and gutta-percha, and then retreated using nickel-titanium (NiTi) retreatment rotary files. The teeth were randomly assigned to four equal groups: control (manual irrigation), ultrasonic irrigation (UI), laser-activated irrigation with a 60 µs pulse duration, and laser-activated irrigation with a 700 µs pulse duration. Irrigation solutions consisted of 17% EDTA and 2.5% sodium hypochlorite. Statistical analysis was performed using SPSS version 21.0. Normality was checked using the Kolmogorov–Smirnov and Shapiro–Wilk tests. Group comparisons were conducted using Dunnett's t-test and the LSD test, with a significance level set at $p \leq 0.05$.

Results: Statistical analysis of scanning electron microscopy (SEM) images revealed superior cleaning efficiency in both laser groups, with a significant improvement in cleanliness rates compared to the other groups. Group 4 (700 µs) achieved the highest percentage of open dentinal tubules (>75%) in the coronal and middle thirds, while Group 3 (60 µs) showed 50– 75% tubule openness. Groups 1 and 2 showed significantly lower cleaning effectiveness, particularly in the apical third.

Conclusion: The pulse duration plays a crucial role in the activation of laser irrigants during root canal retreatment. The 700 µs PIPS activation resulted in better cleaning outcomes compared to the 60 µs laser activation.

Keywords: Er,Cr:YSGG laser, laser-activated irrigation, photoacoustic streaming, root canal irrigants, root canal retreatment, scanning electron microscopy, smear layer removal, ultrasonic irrigation

HIGHLIGHTS

- Laser application in root canal obturation presents a promising approach, enhancing disinfection efficiency and reducing residual bacterial load.
- This study demonstrates that laser irradiation can improve the sealing ability of root canal fillings, potentially minimizing long-term treatment failures.
- Periapical radiography was utilized to accurately assess root canal morphology, providing valuable insights into the effects of laser treatment on canal structure.
- Integrating laser technology into endodontic treatment may offer a viable alternative to conventional techniques, reducing the need for retreatment and improving clinical outcomes.
- The study underscores the need for further clinical research to optimize laser application protocols in endodontics and maximize patient benefits.

INTRODUCTION

Root canal treatment failure represents a major challenge in modern dentistry, with persistent bacterial infections within the root canal system being a primary cause of apical periodontitis. The complexity of this issue is further exacerbated by factors such as inadequate canal filling, overextension of filling materials, improper coronal seals, and procedural errors, all of which contribute to the failure of what is otherwise a

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cost-effective method for tooth preservation (1). Large gaps between filling particles and the canal increase the risk of post-treatment infection (2). Endodontic failure is often caused by a combination of clinical, anatomical, and microbiological factors. The main contributor is persistent microbial infection, particularly in difficult-to-access areas like lateral canals, apical ramifications, and dentinal tubules. Enterococcus faecalis is notably resistant to disinfection protocols, making it a key player in treatment failure. Inadequate cleaning, shaping, and sealing lead to bacteria and debris remaining in the canal, resulting in persistent inflammation. Missed canals, iatrogenic errors, and poor-quality restorations also compromise treatment outcomes. Biofilm formation further protects bacteria from irrigants and medications. Delays in definitive restoration increase the risk of contamination and failure. Addressing these factors is crucial for improving endodontic success (3).

Effective gutta-percha removal is essential in managing failed endodontic treatments. Several methods for gutta-percha removal exist, including mechanical, thermal, chemical, and ultrasonic techniques (1). However, complete elimination is rarely achievable (4). Bioceramic sealers offer two major benefits. Firstly, due to their biocompatibility, surrounding tissues cannot reject them. Secondly, the presence of calcium phosphate in bioceramic materials improves their setting qualities, resulting in a crystalline structure and chemical makeup similar to apatite, found in both teeth and bones (5). However, since bioceramic sealers are hard-setting and insoluble in conventional solvents such as chloroform, concerns about their retreatability persist (6). Gutta-percha can be removed using hand files, solvents, heat, rotary instruments, and ultrasonic equipment (7). Various supplementary techniques, including high-intensity lasers, photodynamic therapy, advanced instruments, and innovative irrigation protocols, have been employed to cleanse dentinal tubules (8). Sodium hypochlorite (NaOCl) is the most frequently used irrigating solution, known for its antibacterial effects and its capacity to efficiently degrade organic dentine, biofilms, and both necrotic and vital pulp tissues (9). EDTA, a chelating agent, is also frequently used for its ability to remove smear layers (9). Penukonda et al. (10) emphasized the importance of EDTA as a chelating agent in their *ex vivo* study, where they investigated smear layer removal. Their findings showed that effective activation techniques significantly enhance EDTA's ability to clean the canal, highlighting the need for its thorough removal to achieve optimal clinical outcomes. Barakat et al. (11) emphasized that rinsing with distilled water after 17% EDTA is crucial to neutralize residual chelating agents, as their presence can compromise the sealing ability of root canal fillings and treatment success. While advancements in irrigation and instrumentation have improved the cleaning and disinfection of the root canal system, complete removal of all obstruction materials during retreatment is still not feasible, necessitating the exploration of additional cleaning methods (12). Since no single solution achieves complete results, a combination of two or more irrigants is essential for safe and effective irrigation (13). Laser-activated irrigation is now recommended for the elimination of gutta-percha. Studies indicate that lasers can melt the gutta-percha material. By combining photothermal and photoablation processes, lasers effectively remove root canal filling material (14). Lasers have proven effective at eliminating sealant and gutta-percha from the root canal system, making them suitable for nonsurgical retreatment (15). In over 70% of cases, filling material could be removed with the Nd:YAG laser at three different output powers (1 W, 2 W, and 3 W), and in 55% of cases, damaged instruments were successfully removed (16). Researchers also found that diode lasers, combined with chloroform and Endosolv E, were significantly more effective for gutta-percha removal (17). The removal of residual iRoot SP and gutta-percha was significantly improved by activating irrigants through photon-induced photoacoustic streaming (PIPS) with the Er,Cr:YSGG laser (18). At a wavelength of 2780 nm, the Er,Cr:YSGG laser is a water-absorbing laser that is safe to use in dentistry without causing temperature elevation, making it suitable for procedures such as veneer removal (19, 20).

The effects of dental lasers on photochemical, photothermal, and photoacoustic processes are actively being researched. One of the main motivations behind laser-activated irrigation (LAI) is to enhance the efficiency of irrigation systems. The Er:YAG laser is used for the novel irrigant activation method known as PIPS (18). PIPS generates cavitation when ablative lasers are used with a water-based solution, producing quick, powerful shock waves that forcefully spread through the entire root canal structure (21). The rapid expansion and collapse of vapor bubbles after 100–200 µs create high pressure, which diminishes as more cavitation effects are produced by the solution re-entering the canal (22). The PIPS technique is particularly effective for activating 17% EDTA in short pulses (60 µs), removing smear layers, especially in the apical region of the tooth (23, 24).

However, carbonization, small fissures, and cracks in the dentine structure may result from laser activation inside the canal (25). The effect of various Er,Cr:YSGG laser parameters, including power and pulse duration, on PIPS technology and tooth structural integrity is not yet fully understood. Research focusing on pulse duration in this context remains limited. This study aims to explore the impact of pulse duration on the removal of residual material during root canal retreatment. The null hypothesis suggests that the pulse duration of the Er,Cr:YSGG laser will not influence the level of cleanliness within the canal. The objective of this study is to evaluate the effect of pulse duration in root canal retreatment using the Er,Cr:YSGG laser for irrigant activation.

MATERIALS AND METHODS

The study was approved by the Research Ethics Committee at the Institute of Laser for Postgraduate Studies, University of Baghdad (Approval No. 1880; Project No. 462, dated 10.10.2023). The Declaration of Helsinki was followed in this investigation.

Sample Selection

To ensure consistent root canal morphology, radiographic evaluation in buccolingual and mesiodistal directions was performed. Only mature, single-rooted maxillary and mandibular premolars with a 12 mm root length and a single canal were included. Teeth with slight curvatures (≈5 degrees) were accepted, while those with complex anatomies, caries, fractures, root resorption, incomplete root formation, or unfavorable canals were excluded. The extracted teeth were stored at room temperature (≈25°C) in distilled water containing 0.1% thymol (Lab Alley, Texas, USA) for two weeks to preserve them and prevent microbial contamination before the experiment. Twenty-eight extracted human single-rooted premolars were randomly assigned into four equal groups (n=7 per group): control (manual irrigation), ultrasonic irrigation (UI), laser-activated irrigation with 60-µs pulse duration, and laser-activated irrigation with 700-µs pulse duration. Random allocation was carried out using a simple randomization method with an online tool (www.randomizer.org). An independent individual who was not involved in the experimental procedures performed the group assignment to ensure allocation concealment and reduce selection bias.

Canals Preparation

To establish a reliable reference for working length (WL) estimation and canal instrumentation, the selected teeth were measured from the anatomical apex using a 12-mm digital caliper (Shahe Tools, Guilin, China). Permanent markers (Yiwu, China) were used to mark the teeth at the start of the procedure. Each root was then sectioned perpendicular to its long axis at the predetermined measurement using a diamond disk (OSA-E28, Osakadent Group Ltd., Guangdong, China) mounted on a cutting machine (Gamberini, Bologona, Italy) with cooling water. A size 10 K-file (Dentsply Maillefer, Ballaigues, Switzerland) was carefully inserted into the root canal until it became visible at the apical foramen, confirming patency, in order to determine the working length. The working length was then calculated by subtracting 1 mm from the length measured at the apical foramen. For canal preparation, the Race Evo system (FKG Dentaire SA, La Chaux-de-Fonds, Switzerland) was utilized, with continuous irrigation using 2.5% sodium hypochlorite (NaOCl) (Cerkamed, Stalowa Wola, Poland), 17% EDTA (Cerkamed, Stalowa Wola, Poland), and regular saline (Pioneer Company, Baghdad, Iraq), adhering to the manufacturer's guidelines for adjusting torque and speed settings while using F3 taper 0.6 files (FKG Dentaire SA, La Chaux-de-Fonds, Switzerland). Irrigation was performed using a 5ml syringe with a 30-gauge side-vented needle, positioned 2 mm short of the working length to ensure proper delivery of the irrigant. After instrumentation, each canal was irrigated with 5ml of sterile water (Pioneer Company, Baghdad, Iraq), followed by 2ml of 2.5% NaOCl and 2ml of 17% EDTA. Finally, three sterile paper points (Diadent X3, Cheongju, South Korea) were used to dry each canal.

Obturation of Canals

Following the single-cone technique, each root canal was filled with a master cone of gutta-percha (GP) size 30 and 6% taper (Dentsply Maillefer, Ballaigues, Switzerland) in conjunction with Total Fill BC Sealer (FKG Dentaire SA, La Chaux-de-Fonds, Switzerland). The GP master cone was carefully fitted to the root canal using the appropriate size to ensure a proper seal. The BC sealer was mixed according to the manufacturer's guidelines and applied to the root canal using a Lentulo spiral (Dentsply Maillefer, Ballaigues, Switzerland). To standardize the sealer quantity, TotalFill BC Sealer was used as per the manufacturer's instructions. The syringe's intracanal tip was placed at the coronal third, and two reference markings of sealer were dispensed into the canal. The excess gutta-percha at the canal orifice was removed using an electrical gutta-percha cutter (Shenzhen, China). The remaining gutta-percha was then vertically compacted using a condenser to ensure proper sealing and adaptation.

To achieve a coronal seal, flowable composite (Filtek Z350, 3M ESPE, St. Paul, Minnesota, USA) was applied to the obturated roots. This step was done to prevent microbial invasion and provide a durable and stable seal in the coronal portion of the root canal.

The samples were then stored in a humidor (KEWEIYIQI, China) at 37°C and 100% relative humidity for three weeks to ensure complete setting of the sealer and proper maturation of the obturation materials.

Retreatment Technique

XP Endo RISE retreatment NiTi rotary files (FKG Dentaire SA, La Chaux-de-Fonds, Switzerland) were used in a crown-down technique to remove the majority of the root filling material from all teeth undergoing conventional retreatment. Afterward, the Race Evo file size 30 with a 0.04 taper (FKG Dentaire SA, La Chaux-de-Fonds, Switzerland) was used to its maximum workable length. The retreatment process was considered complete when the file reached the full working length and no additional filling material was visible.

The 28 teeth were randomly divided into four equal groups of seven, based on the final irrigation technique: Group 1 served as the control group, receiving syringe-based manual irrigation (Pioneer Company, Baghdad, Iraq); Group 2 received ultrasonic irrigation (Woodpecker, Guilin, China).

Pilot Study for Laser Groups

A 2 mm gap was maintained between the laser point and the specimen when the tooth was inserted into an acrylic mold. The laser tip was positioned directly above the root canal orifice during laser activation. To ensure that the laser energy was precisely directed to the area near the canal entrance, the tip remained stationary throughout the procedure and was not advanced apically into the canal. A pilot study was conducted to determine the ideal laser parameters—such as power and pulse repetition rate (PRR)—that would produce the PIPS effect without causing any adverse side effects. The study involved five teeth and examined a range of laser parameters, including PRR of 5 Hz, 1% air, 1% water, and laser powers of 0.1 W, 0.25 W, 0.5 W, 0.75 W, and 1.0 W, using the Er,Cr:YSGG laser. After exposing each specimen to the laser, the roots were sectioned longitudinally, and images were captured at various magnifications (500X, 1000X, 1500X, 2000X, 2500X, and 3000X) using an Axia™ ChemiSEMTM Scanning Electron Microscope (SEM), operating at 100 pA pressure and 3 kV voltage. At least three randomly selected locations from each specimen were analyzed. Based on the results from the pilot study, the final laser settings for the Er,Cr:YSGG laser were set to 1 W, PRR

5 Hz, air pressure at 1%, and water level at 1%. Notably, using a laser power greater than 1 W (such as 2 W) resulted in carbonization of the sample.

Laser parameters:

- Laser Used: Er,Cr:YSGG laser
- Emission Mode: Free running pulse
- On/Off Control: Key switch
- Wavelength: 2780 nm
- Mode: Multi-mode
- Laser Classification: Four
- Energy Density: Energy/Area (Energy=Power/Frequency)

Given these parameters, the energy density was calculated as follows:

- Energy: 1 watt / 5 Hz=0.2 Joules=200 mm Joules
- Area: πr^2=2.810^{-7} cm^2
- Energy Density: 71 mm Joules

Group Irrigation and Laser Treatment Protocols:

Group 1 (control group-manual syringe irrigation)
Using 30-gauge syringes, canals were irrigated with 2ml of 2.5% NaOCl up to 2 mm short of the WL after each filing. After drying the canal with paper points, the canals were irrigated with 1ml of EDTA, followed by 2ml of sterile distilled water.

Group 2 (ultrasonic irrigation)
Each root canal was initially activated with 2ml of 2.5% NaOCl and 1ml of EDTA. Ultrasonic irrigation was performed using an ultrasonic device (U6 LED Woodpecker DBA, China), set to 25% power in E mode at 28 kHz. A size 20, taper 0.02 ultrasonic tip (ESI Instrument, EMS, Le Sentier, Switzerland) was inserted into the canal, 1 mm from the WL, and activated for 20 seconds, ensuring no contact with the canal walls.

Group 3 (laser-activated irrigation - short pulse duration)
The root canals were meticulously irrigated with 2ml of 2.5% NaOCl and 1ml of EDTA, followed by precise irradiation using the Er,Cr:YSGG laser (Waterlase iPlus Biolase, San Clemente, CA, USA). The laser was operated under carefully calibrated parameters to optimize treatment efficacy, ensuring maximal results.

- Power: 1 W
- Frequency: 5 Hz
- Pulse Duration: 60 µs
- Air Pressure: 1%
- Water Level: 1%
- Irradiation Time: 30 seconds
- Tip: MZ6 (Biolase)
- Tip Diameter: 600 µm
- Tip Distance from Root Surface: 2 mm, perpendicular to the root surface

Laser energy and power density calculations for Group 3:

- Energy: 200 mm Joules
- Energy Density: 71×10^4 mm Joules
- Dose: 1.065×10^5 Joules
- Total Irradiation Time: 30 seconds
- Number of Pulses: 150 pulses/sec
- Peak Power: 3.3×10^3 Watts
- Power Density: 1.1×10^6 watts/cm^2

Group 4 (laser-activated irrigation - long pulse duration):
Irrigation was performed with 2ml of 2.5% NaOCl and 1ml of EDTA, followed by irradiation with the Er,Cr:YSGG laser using the following parameters:

- Power: 1 W
- Frequency: 5 Hz
- Pulse Duration: 700 µs
- Air Pressure: 1%
- Water Level: 1%
- Irradiation Time: 30 seconds
- Tip: 600 µm in diameter
- Tip Distance from Root Surface: 2 mm, perpendicular to the root surface

Laser energy and power density calculations for Group 4:

- Energy: 200 mm Joules
- Energy Density: 71×10^4 mm Joules
- Dose: 1.065×10^5 Joules
- Total Irradiation Time: 30 seconds
- Number of Pulses: 150 pulses/sec
- Peak Power: 2.8×10^2 Watts
- Power Density: 1×10^5 watts/cm^2

Post-Irrigation Analysis: After irrigation, each specimen was longitudinally sectioned using carborundum discs, ensuring constant water irrigation to avoid overheating. The sections were then divided into coronal, middle, and apical thirds, with the portion containing the root canal space retained for further analysis. Each tooth was sectioned into three parts—apical, middle, and coronal—resulting in a total of 84 samples prepared for examination. The specimens were subsequently sent for SEM imaging. Finally, two endodontic specialists assessed the SEM images for grading.

Power Analysis Justification
A post hoc power analysis was performed using G*Power software (version 3.1.9.7) to assess the adequacy of the sample size in this study. The analysis was based on key comparisons that showed statistically significant differences, particularly between the Control group (G1) and the Laser 60 microseconds group (G3) in the coronal third region, where the mean difference was 2.00 with a standard deviation of 0.577 (n=7 per group).

The calculated post hoc power for this comparison was 0.98 (98%), exceeding the commonly accepted threshold of 0.80, indicating a high probability that the study had sufficient power to detect meaningful differences.

SEM Analysis

The samples were prepared for analysis using scanning electron microscopy (SEM) with a Thermo Fisher Scientific (Waltham, USA) microscope. After drying, the samples were placed in a vacuum coating system (Angstrom Advanced, Boston, USA), ion sputter and sprayed with a 10–15 nm thick layer of gold. This coating provided a conductive metal layer that minimized charging effects, reduced heat damage, and enhanced the secondary electron signal, which is crucial for the topographic analysis in SEM (26). The sample was placed on the sample holder in a flat position and inserted into the device in a flat manner without any tilting. SEM observations were carried out on the coronal, middle, and apical thirds of each sample at 10 kV and 1000× magnification (25). A total of 4 images per third of the sample were taken. To ensure an unbiased and reliable assessment of the SEM images, two skilled endodontists independently evaluated the images using criteria adapted from Bernardes et al. (27) and Pirani et al. (28), as follows:

- Score 0: More than 75% of the dentinal tubules are open and visible, with no smear layer or filling material present.
- Score 1: Smear layer and debris from the filling material are present in some areas, and less than 75% of the tubules are exposed.
- Score 2: A smear layer and filling debris are frequently present, with less than 50% of the tubules clearly visible in some regions.
- Score 3: The dentine surface is completely covered by a smear layer and filling debris, with no visible tubules.

Statistical Analysis

Data analysis and presentation were carried out using the Statistical Package for Social Sciences (SPSS) version 21.0 (IBM, Armonk, New York, USA). The normality of the data was evaluated using the Kolmogorov-Smirnov and Shapiro-Wilk tests. To compare the tested groups with the control, a t-test for repeated measures was applied. Data are presented as mean±standard deviation (SD), along with additional descriptive statistics.

Multiple comparisons between the groups and the control were conducted using Dunnett's t-test. To determine significant differences between the mean values of the tested groups, the Least Significant Difference (LSD) test was utilized. The letters (A, B, and D) denote the levels of significance, with the most significant results labeled as A, and the significance decreasing with each subsequent letter. A p-value of ≤0.05 was considered statistically significant, while p-values greater than 0.05 (p>0.05) were considered non-significant.

RESULTS

SEM Imaging and Assessment

Representative SEM images were obtained from all thirds of the root canals (Fig. 1).

Coronal third

Group 1 and Group 2: Both groups show similar proportions of filling residue, which is moderate in amount. The mean SEM score for Group 1 was 2.43±0.54 and for Group 2 was 2.43±0.78 (Table 1).

Group 3 and Group 4: The canal walls are almost completely clean, with the remaining filling material being minimal. Group 3 had a mean SEM score of 0.43±0.53 (Table 1), and Group 4 had a mean SEM score of 0.57±0.78 (Table 1), both showing significantly better cleaning than Groups 1 and 2 (p≤0.05).

Statistical Differences

As presented in Table 1 (Fig. 2), there was a statistically significant difference in the SEM scores among the four groups in the coronal third (p≤0.05). However, no significant difference was observed between Group 1 and Group 2, nor between Group 3 and Group 4.

Table 2 (Fig. 2) indicates that Group 4 exhibited a significant difference compared to the other groups in the middle third, while no significant difference was found between Group 1 and Group 2.

In Table 3 (Fig. 2), significant differences were noted across the groups in the apical third, although Groups 1 and 2 showed similar statistical results.

Middle third

Group 1: A smear layer and residual filling material cover the majority of the canal wall.

The mean SEM score was 2.14±0.96 (Table 2).

Group 2: Less filling residue and smear layer are present compared to Group 1. The mean SEM score was 2.57±0.78 (Table 2).

Group 3: Minimal filling residue remains, with a significant number of visible open dentinal tubules. The mean SEM score was 0.86±0.69 (Table 2), significantly cleaner than Groups 1 and 2 (p≤0.05).

Group 4: More than 75% of the dentinal tubules are open, with very little filling residue present. The mean SEM score was 0.70±0.75 (Table 2), showing the best cleaning in the middle third among all groups.

Apical third

Group 1: The apical third shows a substantial amount of smear layer, with most of the dentinal tubules covered by remnants of the root filling material. The mean SEM score was 2.43±0.78 (Table 3).

Group 2: The percentage of open dentinal tubules is significantly less than 50%. Some tubules are partially open, while others remain fully covered by a thick layer of leftover filling material. The mean SEM score was 2.85±0.37 (Table 3).

Group 3: There are trace amounts of filling debris and smear layer, with about 50% to 75% of the dentinal tubules exposed. The mean SEM score was 1.14±1.34 (Table 3), significantly cleaner than Groups 1 and 2 (p≤0.05).

Group 4: Almost all dentinal tubules are exposed, and minimal filling debris remains. The mean SEM score was 0.86±1.46 (Table 3), showing the cleanest result in the apical third compared to other groups.

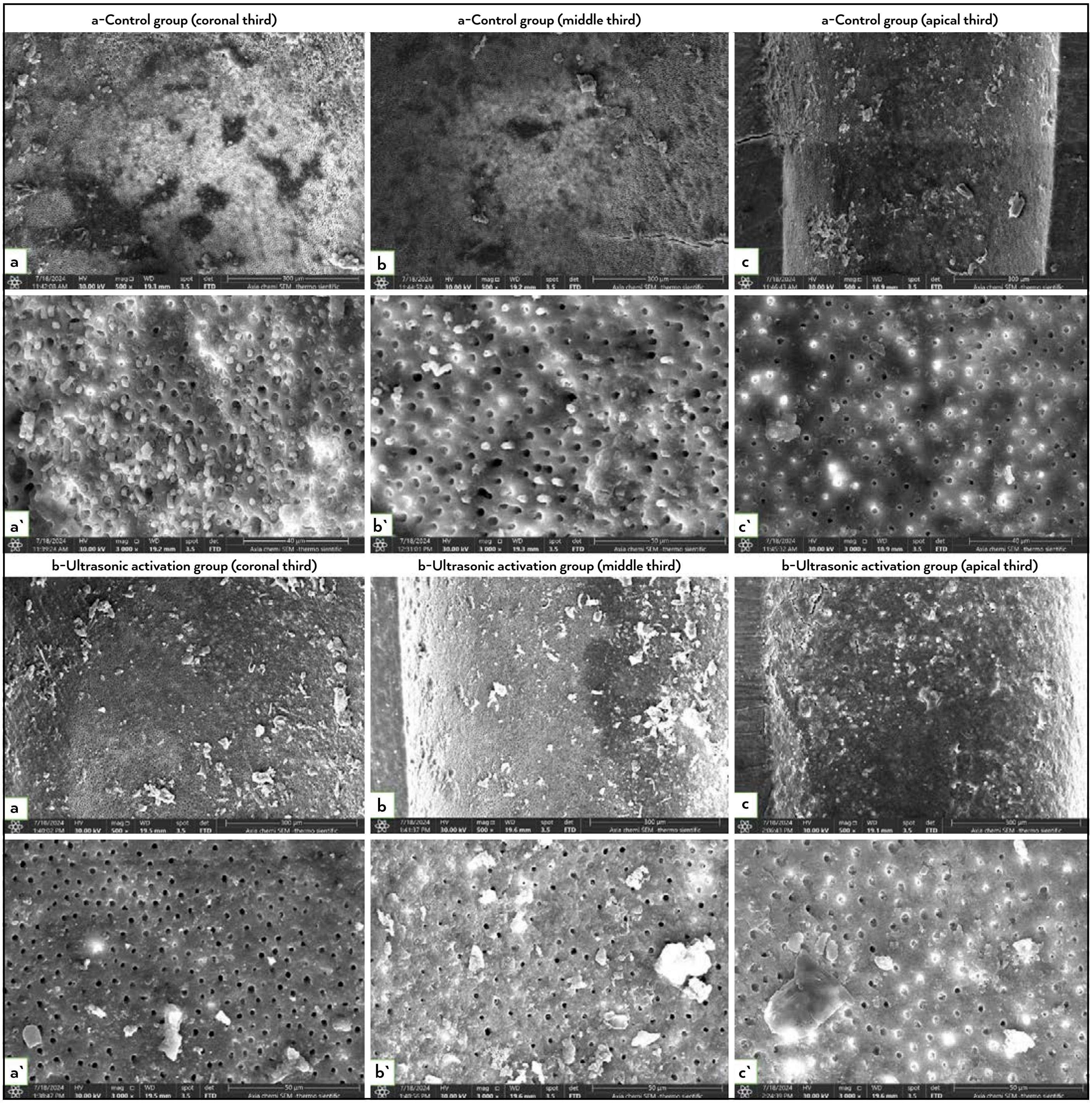

Figure 1. Representative SEM images showing remnants of root canal obturation materials after retreatment procedures. a and a`: Coronal third at magnifications ×500 and ×3000, respectively. b and b`: Middle third at magnifications ×500 and ×3000, respectively. c and c`: Apical third at magnifications ×500 and ×3000, respectively

DISCUSSION

In endodontic therapy, gutta-percha is the most commonly used obturation material, often in combination with various sealers (29). The goal of nonsurgical endodontic retreatment is to eliminate any remaining bacteria or contaminated filling material that could have caused the failure of the previous treatment (30). During the setting procedure, hydroxyapatite forms and chemically interacts with dentinal tubules, allowing bioceramic sealers to adhere to the root canal dentine.

However, one of the main drawbacks of bioceramic sealers (BCS) is their difficulty in removal during retreatment (31). Several factors influence the retreatability of the root canal system, including the type of endodontic sealer used (32). This may explain why BC sealers tend to leave more filler material behind after retreatment than AH Plus or AH-26 sealers (33, 34).

In this study, after longitudinally dividing the samples, residual gutta-percha (GP) and sealer on the canal walls were evaluated through direct visual grading of images obtained

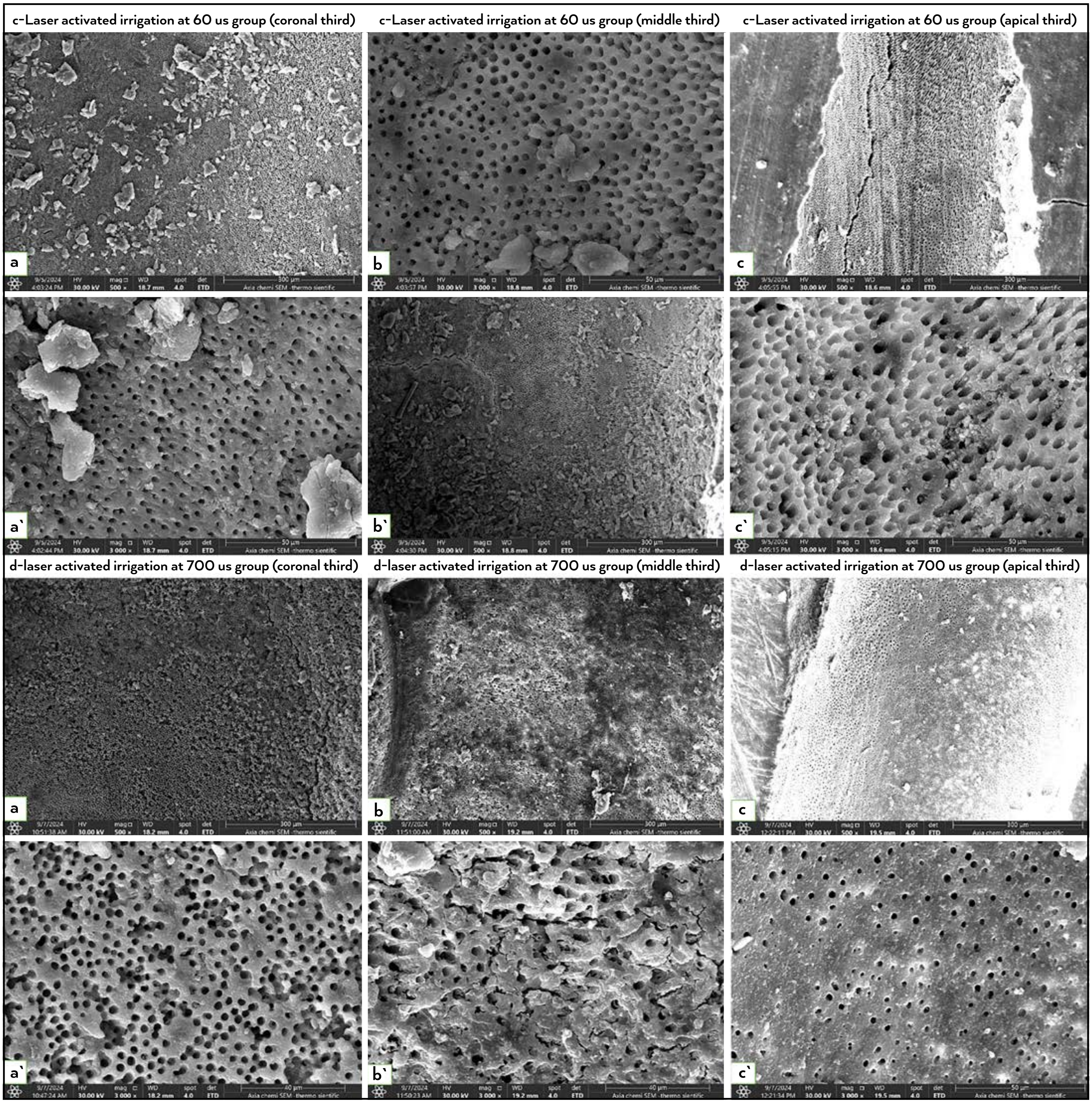

Figure 1 (cont.). Representative SEM images showing remnants of root canal obturation materials after retreatment procedures. a and a`: Coronal third at magnifications ×500 and ×3000, respectively. b and b`: Middle third at magnifications ×500 and ×3000, respectively. c and c`: Apical third at magnifications ×500 and ×3000, respectively

via scanning electron microscopy (SEM). Direct visual scoring is considered a simple and efficient method for assessing such residues (35). During retreatment, Obeid et al. (36) used passive ultrasonic-activated irrigation to remove GuttaFlow Bioseal root canal filling material. They found that while the activation of irrigation techniques was effective, it was insufficient to remove all the filling material from the canal walls. In their study, Yang et al. (17) investigated the effectiveness of standard canal retreatment procedures using nickel-titanium (NiTi) rotary instruments, as well as laser-activated and ultrasonic-activated techniques, to remove the tricalcium silicate-based sealer iRoot SP and gutta-percha *in vitro*. The results revealed that none of the techniques were able to completely eliminate the residual gutta-percha and iRoot SP, emphasizing that root canal retreatment remains a complex procedure that requires more efficient methods.

In this study, after mechanical retreatment, PIPS and ultrasonic-activated irrigants were used as supplementary techniques to eliminate any remaining gutta-percha and BC sealer. None

TABLE 1. Residual filler material's mean and standard deviation (SD) for each group in the coronal third of the root canal

Coronal third	G1 control	G2 ultrasonic	G3 laser 60 µs	G4 laser 700 µs
N	7	7	7	7
Mean±SD	B	B	A	A
	2.43±0.54	2.43±0.78	0.43±0.53	0.57±0.78
		p=0.001		

LSD test was used to calculate the significant differences between the tested mean, the letters (A and B) represented the levels of significance. Similar letters mean there are no sig differences between the tested mean. P≤0.05 were considered significantly different

TABLE 2. Residual filler material's mean and standard deviation (SD) for each group in the middle third of the root canal

Middle third	G1 control	G2 ultrasonic	G3 laser 60 µs	G4 laser 700 µs
N	7	7	7	7
Mean±SD	C	C	B	A
	2.14±0.96	2.57±0.78	0.86±0.69	0.7±0.75
		p=0.001		

LSD test was used to calculate the significant differences between the tested mean, the letters (A, B and C) represented the levels of significance. Similar letters mean there are no sig differences between the tested mean. LSD: Least significant difference. P≤0.05 were considered significantly different

TABLE 3. Residual filler material's mean and standard deviation (SD) for each group in the apical third of the root canal

Apical third	G1 control	G2 ultrasonic	G3 laser 60 µs	G4 laser 700 µs
N	7	7	7	7
Mean±SD	C	C	B	A
2.43±0.78	2.85±0.37	1.14±1.34	0.86±1.46	
		p=0.001		

LSD test was used to calculate the significant differences between the tested mean, the letters (A, B and C) represented the levels of significance. Similar letters mean there are no sig differences between the tested mean. P≤0.05 were considered significantly different

of the procedures, except for the ones employing PIPS, were able to completely remove the residual BC sealer and gutta-percha, as demonstrated by our results. The PIPS technique enhances fluid exchange and debris removal by generating vapor bubbles that create secondary cavitation effects (37).

Pulse duration is an important factor in PIPS technology, as shorter pulse durations lead to high power densities (38). According to the SEM results, there were significant differences in the scores of the four groups across the coronal, middle, and apical thirds of the root canal. The PIPS groups demonstrated the highest levels of cleanliness, while the control group had the lowest. In the apical third, the first group showed that the majority of the dentinal tubules were covered with remnants of root filling material, and a significant amount of smear layer was also present. The second group had a much lower percentage of open dentinal tubules, with some being completely covered by a thick layer of residual filling material, while others were only partially open. The third group exhibited between 50% and 75% of exposed dentinal tubules, with trace amounts of filling debris and smear layer still present.

For the middle third: Group 1: The majority of the canal wall is covered with smear layer and filler material residues. Group 2: There is reduced smear layer and filler residue. Group 3: A considerable number of open dentinal tubules are visible, and filling residue is barely noticeable. Group 4: There is very little filling residue, as more than 75% of the dentinal tubules are open. In the coronal third, the proportions of residue in Groups 1 and 2 were almost identical, as the filling residue was moderate. However, the third and fourth laser groups showed nearly perfect results for the canal wall. Galler et al. (39) demonstrated that PIPS was associated with deeper penetration of irrigants into dentinal tubules, which makes lasers a more effective cleaning method than traditional techniques. Lasers are particularly advantageous because they do not rely on the insertion depth of files or probes, which is especially important in the apical part of the tooth, the most difficult region to clean. Typically, PIPS uses an Er,Cr:YSGG laser for root canal irrigation. This laser emits energy that is largely absorbed by water, requiring only a small amount of energy to provide an effective activation-irrigation effect.

Recent research has examined additional irrigation-enhancing methods that could serve as useful supplements in endodontic retreatment, which aligns with our findings. A novel ultrasonic irrigation system was introduced by Fekrazad et al. (40), which simultaneously activates the irrigant ultrasonically and delivers it continuously. This technique enhanced the disruption and elimination of residual materials, especially in complex anatomical areas. Similarly, a comprehensive review by Skvrce et al. (41) demonstrated the effectiveness of passive ultrasonic irrigation (PUI) in removing root canal filling residues, particularly in the apical third, due to improved acoustic micro streaming and cavitation effects.

These alternative approaches further reinforce the importance of irrigant activation in enhancing canal cleanliness. When considered alongside the current study's use of PIPS, these methods collectively demonstrate that combining energy-based irrigation with optimal parameters enables the irrigant to reach remote and challenging areas within the root canal system. This results in more effective removal of filling materials, superior disinfection, and, ultimately, a higher likelihood of successful retreatment outcomes.

In Group 3, the study showed that using 1 watt, 5 Hz, air=1%, water=1%, and an exposure time of 30 seconds with a short pulse duration of 60 µs was effective for achieving the PIPS effect and removing remnants from the canal walls. However, some drawbacks were observed, such as carbonization near the canal orifice, which was visible to the naked eye during the procedure. This is likely due to the short pulse duration, which did not allow the force to reach all areas of the canal and instead mainly affected the crown. Therefore, to ensure the force is adequately distributed throughout the root, the pulse dura-

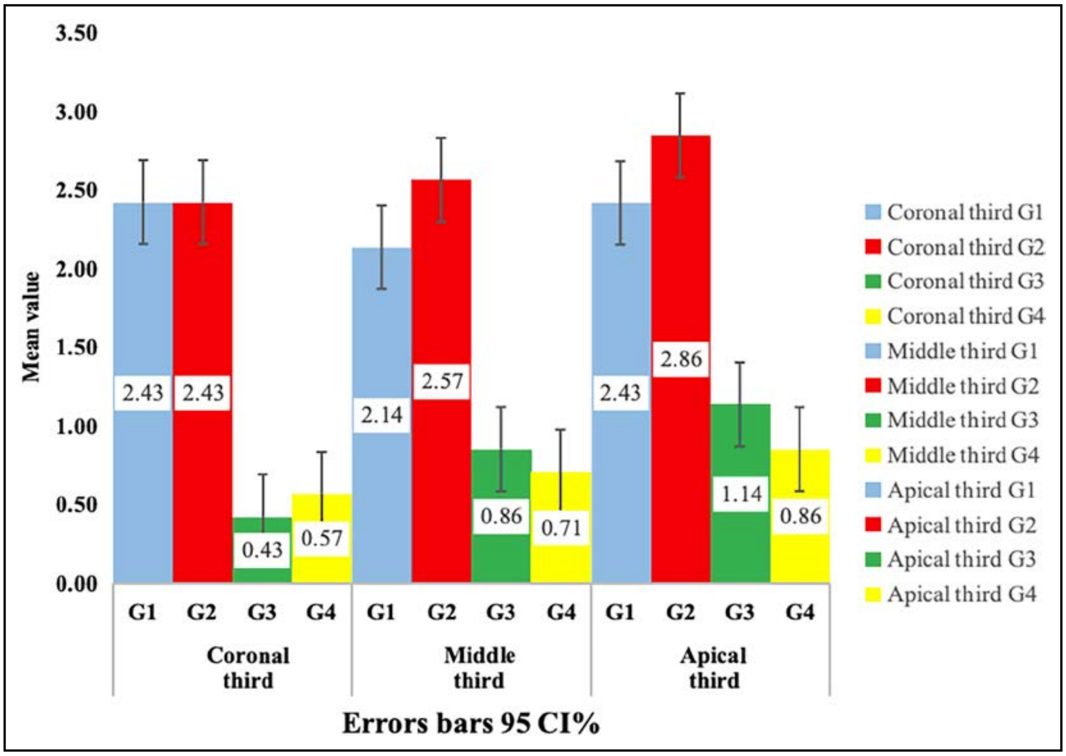

Figure 2. Bar chart showing the mean percentages of remaining root canal filling material in the coronal, middle, and apical thirds for each study group after retreatment. Error bars represent standard deviations. Statistical significance between groups is indicated where applicable

CI: Confidence interval

tion needs to be lengthened. For Group 4, the laser parameters were set to power=1 W, frequency=5 Hz, air=1%, water=1%, exposure time=30 seconds, and a longer pulse duration of 700 µs to avoid the adverse effects of carbonization. This longer pulse duration allows the energy to be absorbed by the irrigant and reach all parts of the tooth effectively, providing a better cleaning effect without accumulating power in any specific area. This explains the significant differences observed between laser groups, particularly in the middle and apical thirds, and the lack of significant differences in the coronal third.

Thus, the null hypothesis, which stated that pulse duration would not affect the cleanliness of the root canal, is rejected.

Safety during endodontic retreatment may be enhanced by using a low-concentration NaOCl solution, which can yield the best results. The PIPS technique, when combined with 2.5% NaOCl and 17% EDTA, has been shown to facilitate the dilation of dentinal tubules, enhancing the penetration of the irrigants and significantly reducing the smear layer and debris from filling materials on the canal walls (15). Given these results, using PIPS to activate 2.5% NaOCl and 17% EDTA may serve as an effective adjunct to remove residual gutta-percha and tricalcium silicate-based sealers after employing NiTi instruments in endodontic retreatment.

Changing the length of the laser pulse during endodontic retreatment has significant clinical implications. Shorter pulse lengths (60 µs, for example) might provide powerful photomechanical effects, but they can also concentrate energy at the coronal level, which could result in surface carbonization and restricted irrigant penetration into deeper canal sections. Longer pulse lengths (such as 700 µs), on the other hand, allow for more regulated and extensive energy delivery, improving irrigant activation across the root canal system without producing undesired heat effects.

Because of its better distribution, the irrigating solution can reach deeper, more difficult-to-reach areas of the root canal that are usually difficult to clean using traditional techniques. This enhances the whole disinfection process by more successfully removing bacterial biofilms and leftover filling materials. The success of a future obturation depends on this improved cleanliness, which also lowers the likelihood of retreatment failure and improves long-term treatment results.

A limitation of this study is its restriction to single-rooted, straight canals in extracted teeth. These controlled conditions may not fully reflect the clinical complexity of curved or multi-rooted canal systems. Therefore, further research involving more anatomically diverse samples is recommended to validate the findings and enhance their clinical relevance.

The study's limitations included the possibility of microscopic residues forming during the cutting stage, which could impair the precise outcome of the amount of cleanliness inside the root canal after cutting. This was reduced by inserting a paper point inside the root canal while cutting.

The number of dentinal tubules varies from person to person, which is another constraint. This has been dealt with by ignoring teeth that had an abnormally high number of dentinal tubules. There is also a limitation: using power above 1 W can lead to carbonization of the tooth, and it becomes prone to fracture. Pulse duration limitations where an increase in pulse duration leads to an increase in power density, which negatively affects when it exceeds the threshold.

CONCLUSION

Based on the extracted results, it can be concluded that laser-activated irrigation has a significant impact on root canal retreatment. The pulse duration plays a crucial role in the activation of irrigants by the laser during the retreatment process. Group 4, with a pulse duration of 700 µs, demonstrated a better effect compared to Group 3, which had a 60 µs pulse duration. This is because the longer pulse duration in Group 4 provided sufficient time for the energy to be effectively transmitted throughout the liquid-filled areas of the canal.

Disclosures

Ethics Committee Approval: The study was approved by the University of Baghdad, Institute of Laser for Postgraduate Studies Research Ethics Committee (no: 1880, date: 10/10/2023).

Informed Consent: Informed consent was obtained from all participants.

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