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Research Article

Removing Bioceramic Sealer Remnants using Er,Cr:YSGG laser Irradiation with PIPS Process: In Vitro Study

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Abstract: Background: This vitro study investigated the effectiveness of Er,Cr:YSGG laser-activated irrigation in removing root canal filling remnants during endodontic retreatment. The technique used photon-induced photoacoustic streaming (PIPS) at 700 µs pulse duration to activate 2.5% sodium hypochlorite (NaOCl) and 17% EDTA. **Materials and methods:** Twenty-one extracted human maxillary and mandibular premolars with single roots were instrumented and obturated using gutta-percha and a bioceramic root canal sealer. After retreatment using nickel-titanium rotary files (XP-endo Retreatment), the specimens were randomly assigned into three groups (n=7 per group) according to the irrigation technique: Group 1: conventional syringe irrigation (control), Group 2: passive ultrasonic irrigation, Group 3: laser-activated irrigation using Er, Cr:YSGG laser (2780 nm, 700 µs pulse duration, 5 Hz, 1 W, RFT2 tip, with no air or water spray). All samples were sectioned longitudinally and examined under a scanning electron microscope (SEM) to assess the presence of residual filling materials in the coronal, middle, and apical thirds. Cleanliness scores were assigned by two calibrated endodontists based on a 4-grade scoring system and were statistically analyzed using one-way ANOVA followed by Tukey's post hoc test. The significance level was set at $\alpha = 0.05$. Statistical analysis revealed a significant difference among the groups ($P < 0.05$). Group 3 showed significantly lower residual debris compared to Groups 1 and 2 across all root thirds, while the difference between Groups 1 and 2 was not statistically significant ($P > 0.05$).
Results: Group 3 (n = 7) exhibited significantly lower residual debris compared to Groups 1 and 2 across all canal thirds ($P < 0.05$). The mean cleanliness scores were highest in the coronal third, followed by the middle and apical thirds. No statistically significant differences were observed between Group 1 and Group 2 ($P > 0.05$), suggesting limited effectiveness of ultrasonic irrigation compared to laser activation.
Conclusion: The use of Er,Cr:YSGG laser-activated irrigation with PIPS at a 700 µs pulse duration, combined with 2.5% NaOCl and 17% EDTA, significantly improved the removal of root canal filling remnants during retreatment. These findings suggest that laser-activated irrigation may serve as an effective adjunct to conventional retreatment protocols, offering enhanced cleaning efficacy across all canal levels.

Keywords: Er,Cr:YSGG, PIPS, pulse duration, retreatment. irrigants.

1. Introduction

Thorough cleaning of the endodontic therapy to be successful, the root canal system must be obturated in three dimensions [1]. This includes the dentinal tubule system and proper filling of the canal. Nevertheless, treatment may still fail even when appropriately performed [2]. Gutta-percha remains the most commonly used obturation material in conjunction with various sealers [3]. However, large voids between the filling material and the canal walls may increase the risk of post-treatment disease [4]. In the event of failure, nonsurgical root canal retreatment is often considered the most viable solution,

particularly when technical errors are the cause. This process involves removal of the old root canal filling material, followed by disinfection and re-obturation of the canals [5]. According to the American Association of Endodontists' Glossary of Endodontic Terms, nonsurgical retreatment includes complete removal of the original root filling material, reinstrumentation, and refilling of the canal system [6].
Total Fill BC Sealer (FKG, Switzerland) is a pre-mixed, injectable, radiopaque, hydrophilic bioceramic sealer that relies on dentinal tubule moisture to initiate and complete its setting reaction [7]. The removal of root filling materials can be achieved using a wide range of instruments and techniques, including hand files, Gates-Glidden burs, heat carriers, nickel-titanium (NiTi) rotary systems, ultrasonics, lasers, and various solvents [8]. Recently, specialized NiTi instruments have been developed for this purpose, such as the XP-endo Finisher R (FKG Dentaire, Switzerland), which changes shape in response to body temperature due to its MaxWire alloy [9].

Effective irrigation is another critical component of successful retreatment. Passive ultrasonic irrigation (PUI) has proven effective in removing tissue remnants, debris, and medicaments from the canal system [10]. A combination of irrigants is typically required, as no single solution is adequate on its own [11]. Sodium hypochlorite (NaOCl) has been widely used as an endodontic irrigant since the mid-20th century due to its antimicrobial properties and ability to dissolve organic tissue [12].
In recent years, laser-activated irrigation has been introduced to enhance irrigant effectiveness [13]. Photon-induced photoacoustic streaming (PIPS) is one such innovation, utilizing laser-generated shockwaves to improve fluid dynamics within the canal [14]. The Er,Cr:YSGG laser (2780 nm) exhibits high absorption in water, making it suitable for activating irrigants. Compared to other lasers like Er:YAG, it produces efficient energy absorption (400 mm^{-1} for Er,Cr:YSGG vs. 1200 mm^{-1} for Er:YAG) with minimal heat generation due to its pulsed emission mode [15].

Additionally, it has been demonstrated that veneer surfaces can be safely and repeatedly heated with this laser type without causing fractures [16, 17]. Histological studies report that pulpal responses to Er,Cr:YSGG laser exposure are minor and reversible, comparable to those seen with high-speed rotary instruments [18]. PIPS uses a laser fiber tip placed in the pulp chamber, reducing the risk of heat transmission to periapical tissues [19]. When used with 17% EDTA, Er,Cr:YSGG laser activation (5 Hz, air/water off, short pulse duration) effectively removes smear layers [20, 21].
Scanning electron microscopy (SEM) is a standard method to evaluate root canal cleanliness, allowing assessment of remaining filling materials and smear layer removal [22]. Yang et al. [23] demonstrated that activating 2.5% NaOCl and 17% EDTA with PIPS significantly improved the removal of iRoot SP sealer and gutta-percha compared to PUI and conventional syringe irrigation (CSI). Similarly, Almohareb et al. [24] evaluated the efficacy of diode laser and ultrasonic irrigation for retreatment of BC sealer and gutta-percha-filled canals, noting no added benefit from surfactants.Despite promising findings, the optimal laser parameters for PIPS using the Er,Cr:YSGG laser remain unclear, particularly regarding the removal of BC sealer and gutta-percha from complex root canal systems.

Thus, the aim of in vitro study was to determine the most effective laser settings for Er,Cr:YSGG PIPS irrigation to improve the removal of residual filling materials during root canal retreatment, in comparison with conventional syringe irrigation and passive ultrasonic irrigation.

2. Materials and Methods

This investigation followed the Declaration of Helsinki. Ethical approval for the procedures of the present study was obtained (10-2023-462).

2.1 Sample selection

A total of 21 extracted human single-rooted premolars with mature apices, straight canals (curvature ≤ 5°), and standardized root length of 12 mm were selected based on radiographic evaluation in both buccolingual and mesiodistal directions. Teeth with root caries, fractures, internal/external resorption, previous endodontic treatment, calcifications, or complex root anatomy were excluded.

Following extraction, all teeth were stored at 25 ± 1 °C in 0.1% thymol solution for no longer than two weeks to prevent microbial growth while maintaining tooth integrity.

2.2 Preparation of samples

All specimens were decoronated at the cementoenamel junction using a diamond disk under constant water cooling to obtain standardized root segments (12 mm). A size #10 K-file was introduced until it was visible at the apical foramen to confirm patency. The working length (WL) was determined by subtracting 1 mm from this measurement.

The 21 teeth were randomly divided into three experimental groups (n = 7) using simple randomization via an online software tool (www.randomizer.org). Allocation concealment was ensured through sealed opaque envelopes, and group assignment was performed by an independent operator not involved in the experimental procedures. All instrumentation, irrigation, and evaluation steps were performed under the same environmental conditions (room temperature: 25°C; relative humidity ~60%).
A closed system was created by sealing the canal apex with softened wax to prevent irrigant extrusion during activation and to ensure stable positioning of the specimens within the custom-made acrylic mold. While this method may slightly alter apical fluid dynamics, it is a commonly accepted practice in in vitro studies to maintain consistent internal conditions and focus the evaluation on intracanal efficacy.
Root canal preparation was performed using the Race Evo rotary system (FKG Dentaire SA, Switzerland) with a crown-down technique. The working length (WL) was established by inserting a #10 K-file (Dentsply Maillefer, Switzerland) into the canal until visible at the apical foramen, then subtracting 1 mm. All instrumentation procedures were performed in a room-temperature-controlled environment (25 ± 1 °C) with adequate lighting.

The canal was shaped up to size 30, taper 0.06. Throughout preparation, each canal received copious irrigation using a 30-gauge side-vented needle (NaviTip, Ultradent, USA) positioned 2 mm short of WL. Irrigants used included:
2.5% Sodium Hypochlorite (NaOCl) (Cerkamed, Poland): 5 mL per canal during shaping.
The pH of the sodium hypochlorite solution was approximately 12.
17% EDTA (Cerkamed, Poland): 2 mL after shaping.
Sterile saline (Pioneer, Iraq): 5 mL as a final rinse.

The total irrigation time per canal was approximately 90 seconds. Each irrigant was delivered slowly over 15–20 seconds per mL to allow optimal contact time. After irrigation, canals were dried using three sterile absorbent paper points (Diadent X3, Korea). Canals were obturated using the single-cone technique with size 30/.06 gutta-percha cones (Dentsply Maillefer, Switzerland) and TotalFill BC Sealer (FKG Dentaire SA, Switzerland). The sealer was introduced into the canal using a Lentulo spiral, and a pre-fitted GP cone was inserted to full WL. Excess GP was seared at the orifice using a heated instrument and vertically compacted with a plugger. To prevent coronal leakage, flowable composite (Filtek Z350 XT, 3M ESPE, USA) was applied over the canal orifice and light-cured for 20 seconds. All specimens were then stored in a humidor (KEWEIYIQI, China) at 37°C and 100% relative humidity for 3 weeks to ensure complete setting of the bioceramic sealer. To ensure outcome assessor blinding, the coded specimens were anonymized by an independent operator prior to the retreatment and SEM evaluation stages.

2.3 Retreatment technique

The root canal retreatment was performed using the XP-Endo RISE NiTi rotary retreatment system (FKG Dentaire SA, Switzerland) with a crown-down technique following the manufacturer's instructions. Initially, the bulk of the root filling was removed using the retreatment files, then final shaping was completed with a Race Evo file size 30 and 0.04 taper to the full working length. Retreatment was considered complete when no visible filling material remained on the canal walls as confirmed under magnification. Following instrumentation, samples were randomly allocated into three groups (n=7 per group) according to the final irrigation and activation protocol used.

Group 1: Manual Syringe Irrigation (Control)

Canals were irrigated using a 30-gauge side-vented needle placed 2 mm short of the working length. After each file, 2 mL of 2.5% NaOCl was delivered over approximately 20 seconds, followed by drying with paper points. Subsequently, 1 mL of 17% EDTA was introduced and left in the canal for 60 seconds to allow adequate chelation. Finally, 2 mL of sterile distilled water was used to flush out residual irrigants [25].

Number of irrigation cycles: 3 per canal
Total irrigation time: ~3 minutes
Temperature and humidity: Room temperature (~25°C), humidity controlled.
Group 2: Passive Ultrasonic Irrigation (PUI)
Following conventional irrigation as in Group 1, the canals were activated ultrasonically using an ultrasonic device (Woodpecker U6 LED, China) set at 25% power in E mode (28 kHz). A size 20 ultrasonic tip (taper 0.02) was inserted 1 mm short of the working length without contacting canal walls and activated for 20 seconds per cycle.
Irrigants: 2 mL 2.5% NaOCl + 1 mL 17% EDTA
Number of activation cycles: 3 per canal
Total activation time: 60 seconds
Environmental conditions: Controlled at room temperature (~25°C)

2.4 Pilot study for laser group

An acrylic mold was used to set the teeth in to be used in a pilot study to determine the ideal laser settings, such as power and pulse repetition rate (PRR), that produce the PIPS effect without having any negative side effects. Five roots of teeth were used, and a range of laser characteristics, such as PRR 5 Hz, 1% air, 1% water, and laser power (0.1 W, 0.25 W, 0.5 W, 0.75 W, and 1.0 W), were used to evaluate the Er.Cr:YSGG laser parameters. Following radiation exposure, the best view was acquired at various magnifications (500X, 1000X, 1500X, 2000X, 2500X, and 3000X) using an AxiaTM ChemiSEMTM Scanning Electron Microscope operating at 3 KV voltages and 100 pA pressure settings. SEM images of at least three randomly selected areas (coronal, middle, and apical) from each specimen were obtained. The pilot study test results were used to define the final laser settings for the Er.Cr:YSGG laser, which were (1w), PRR 5 Hz, Air: 1%, and Water: 1%. When using more than 1 watt, carbonization of the sample is noticed.

Group 3 (laser-activated irrigation with Er,Cr:YSGG 2780 nm for 700 us pulse duration):
Laser parameters for group 3
Power =1 W
Frequency = 5 Hz
Air= 1%
Water=1%
Pulse duration = 700 us
Energy = 200 mm Joules
Energy density =71 ×104 mm Joules
Dose=1065 ×105 Joules
Irradiation time = 30 seconds
Number of total pulses = 150 pulse/sec.
Peak power =2.8×10 2 watts
Power density =1×105 watts/cm2

A 2,780 nm Er, Cr: YSGG laser (Waterlase iPlus Biolase, San Clemente, CA, USA) was used to pulse the samples. Its settings were 1 watt, 700 µs of pulse duration, 5 Hz repetition frequency, 1% air, and 1% water level. Using a 600 µm tip diameter (Biolase, San Clemente, CA, USA), samples were exposed to radiation for thirty seconds in this examination before an irrigant was placed into the canal. The tip was parallel and 2 mm distant from the root surface and perpendicular to it. Following the tooth's longitudinal

sectioning, it was separated into the coronal, middle, and apical thirds. The tooth's portion with the root canal space was kept, while the region with the faint canal was discarded. The root specimen was then sent for SEM examination. All specimen allocations and irrigation procedures were performed by an operator blinded to the study hypothesis. Post-treatment, the samples were coded and assessed by two independent endodontic specialists who were blinded to group assignment. The entire procedure was conducted in a laboratory environment controlled for temperature (25 ± 1 °C) and relative humidity (50–60%) to minimize variability and ensure reproducibility.

2.5 Power Analysis Justification

A post hoc power analysis was conducted using G*Power software (version 3.1.9.7) to evaluate the adequacy of the sample size used in this study. The analysis focused on the comparison between the control group (G1) and the Laser 700 microseconds group (G3) at the coronal third level, where the mean difference was 2.00 with a standard deviation of 0.577 (n = 7 per group). The resulting post hoc power for this comparison was calculated to be 0.98 (98%), which exceeds the commonly accepted threshold of 0.80. This indicates that the study had sufficient statistical power to detect significant differences and minimize the risk of Type II error.

3. SEM analysis

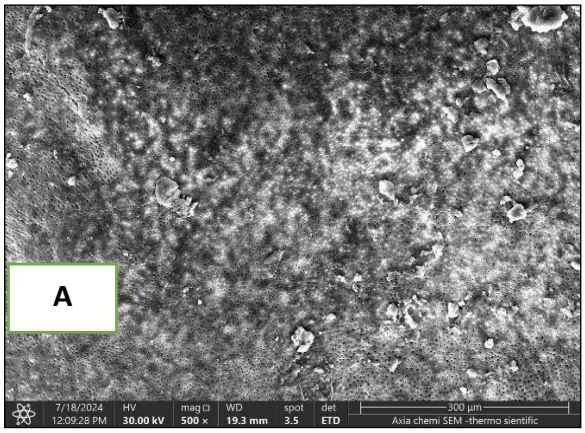
Thermo Fisher Scientific's (Waltham, USA) scanning electron microscopy (SEM) equipment was used to prepare the samples for examination. After dehydrating the samples, they were put in an ion sputter vacuum system coating apparatus (Ngstrom Advanced) and sprayed with a layer of gold 10–15 nm thick. This created a conductive metal layer on the sample, which helped to restrict charging, reduce heat damage, and boost the secondary electron signal required for SEM topographic analysis [26]. The coronal, middle, and apical thirds of each sample were then subjected to SEM analyses at 10 kV and 1000× magnification [27]. A total of 4 images per third of the sample were taken. SEM images were captured at various magnifications (×500, ×1000, ×2000, and ×3000) to allow detailed observation of the canal wall cleanliness and dentinal tubule exposure. The same magnification was used consistently across samples for each corresponding canal third (coronal, middle, apical) to enable accurate and standardized visual comparison. To determine a blind score for the SEM images [23], two endodontists adapted criteria based on Bernardes et al. and Pirani et al. [23] as follows: Score 1: Less than 75% of the tubules are visible due to debris in the smear layer and filler material in some areas. Score 2, with less than 50% of tubules visible in a limited area, and score 3, with a smear layer and infill debris usually present. Tubules are not apparent; all dentin has a smear layer and filling debris. Score 0: In case zero, more than 75% of the tubules are visible and open, and no smear layer or filler material is present.

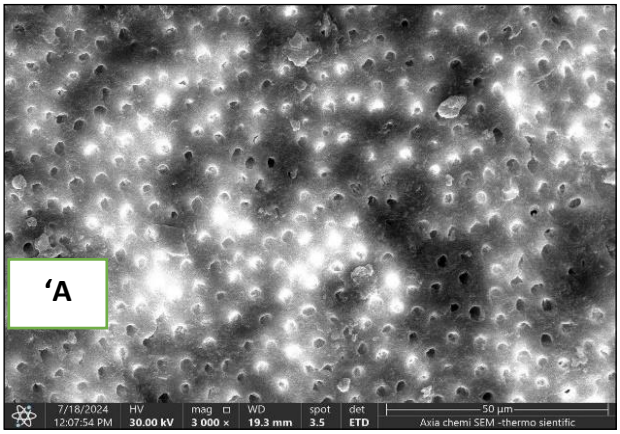
In addition to the visual scores, a quantitative analysis of residual contamination was performed using ImageJ software (NIH, USA). Each SEM image was analyzed to calculate the percentage of the canal wall area covered by residual sealer or debris relative to the total observed dentinal area. This provided a numerical contamination index for each image, supplementing the visual scores with objective data. All SEM findings were compiled into comparative tables presenting both the mean qualitative scores and quantitative contamination percentages for each group across the coronal, middle, and apical thirds. These tables allowed for detailed visual and statistical comparisons.

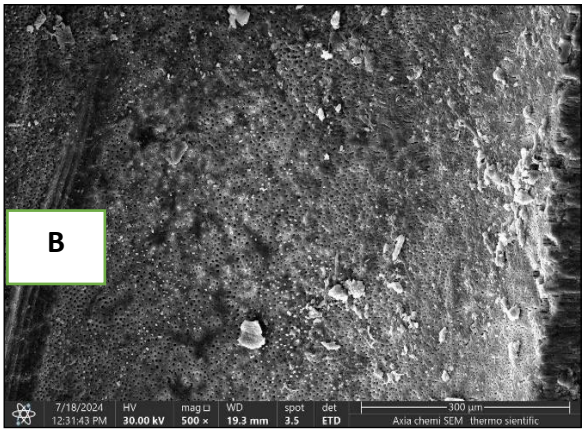
Representative SEM images are presented in Figure 1, showcasing typical canal surfaces from each third and treatment group. For instance, Figure 1A (Group I, apical third) exhibits heavy coverage with residual sealer and no visible tubules, indicating a score of 3 and a high contamination percentage. In contrast,

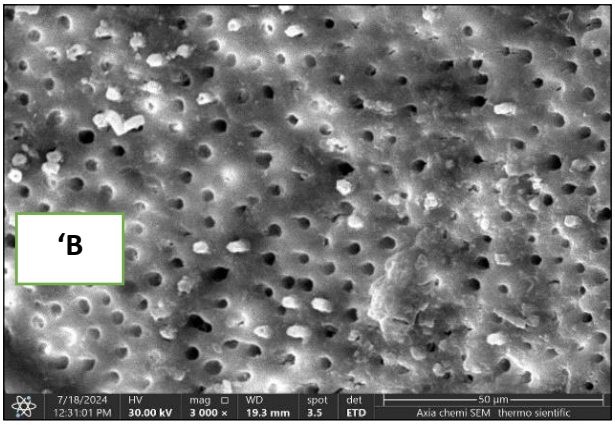
Figure 1B (Group II, coronal third) shows a surface with mostly open tubules and minimal debris, corresponding to a score of 0. The cleaning efficacy observed in this study, especially with laser-assisted protocols, is in agreement with previous SEM analyses reported by Bernardes and Pirani et al. [23], who noted enhanced smear layer removal in the apical third using Er:YAG laser techniques and emphasized the limitations of conventional irrigation in reaching the apical third.

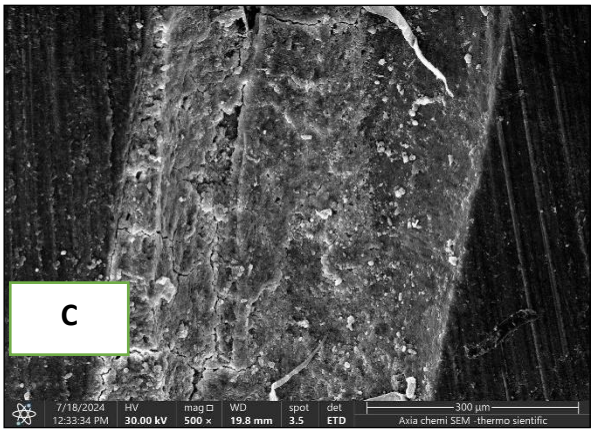
A-control group

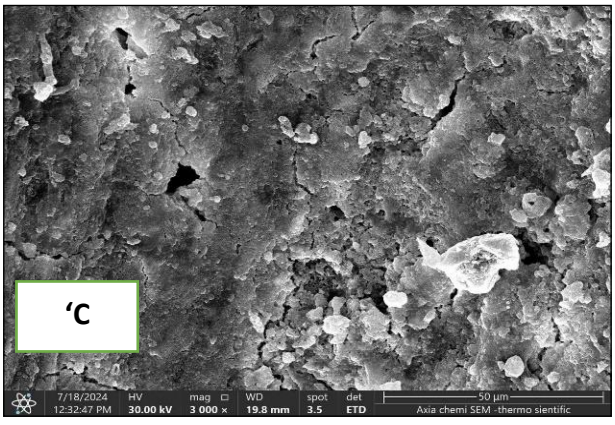




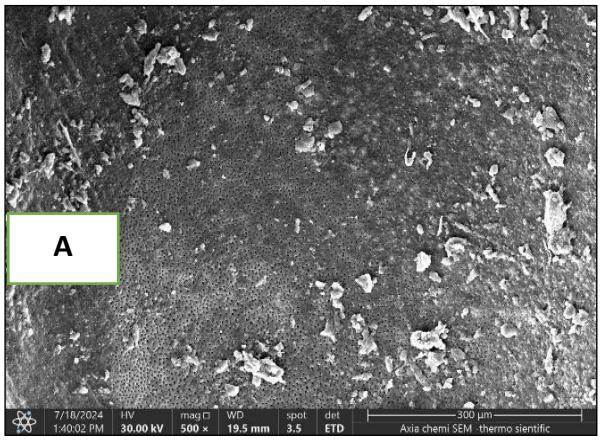


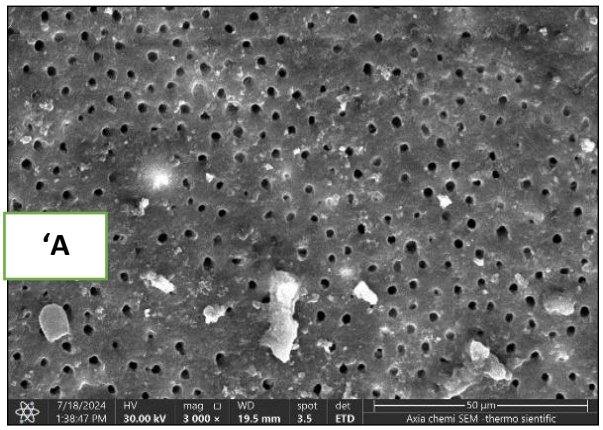


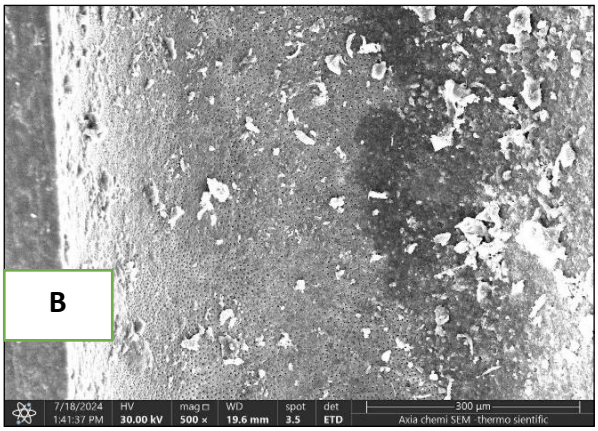


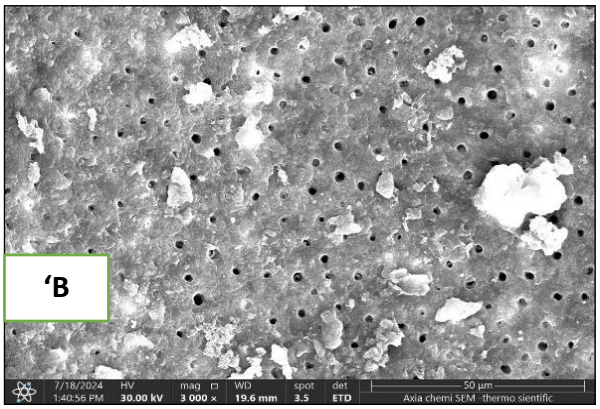


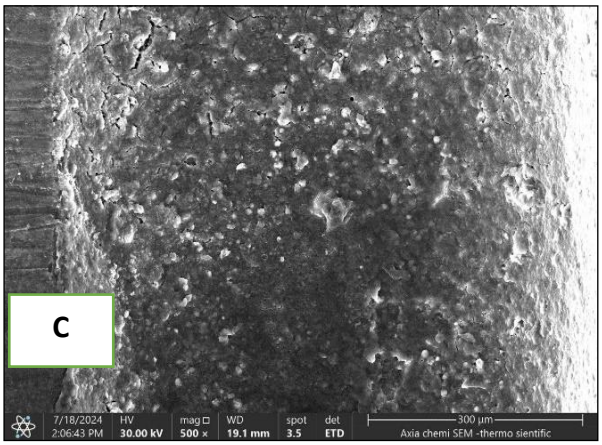
B-Ultrasonic activation group

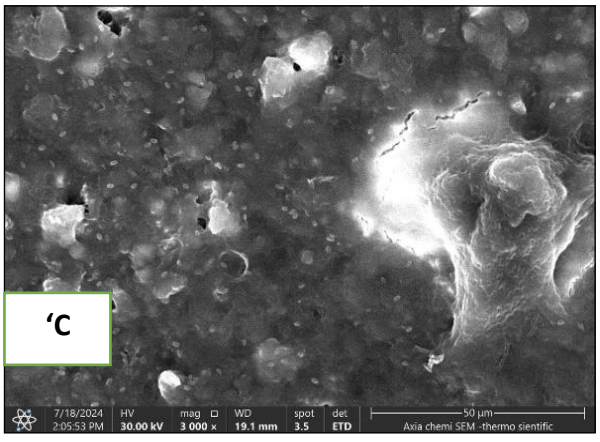












C-laser activated irrigation at 700 us group

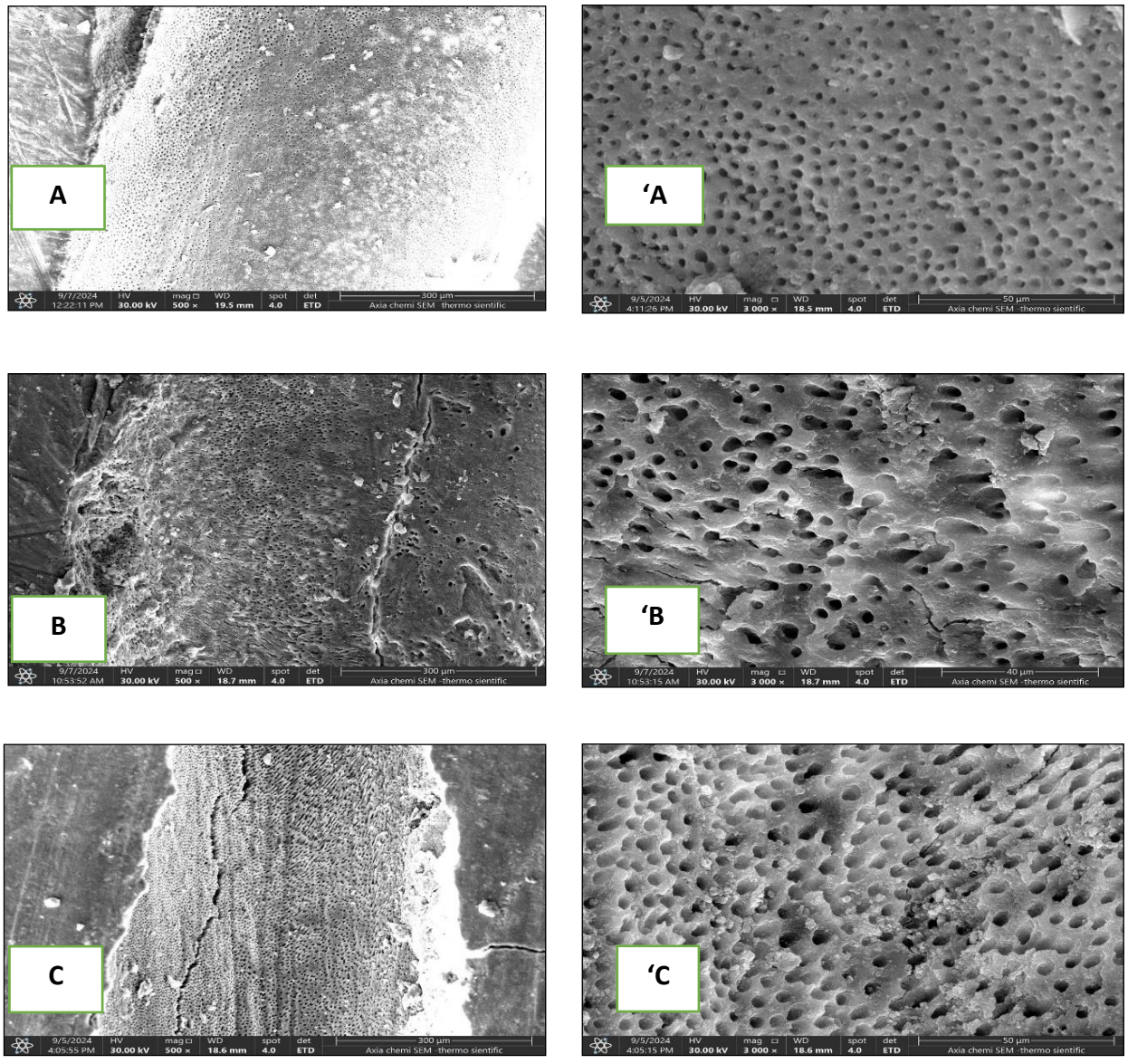


Figure 1: SEM images of the obturation materials remnants after retreatment A. Coronal third at (500x) 'A coronal third at (3000x), B. Middle third at (500x) 'B middle third at (3000x), Apical third at (500x) 'C apical third at (3000x).

4. Statistical Analysis

Statistical analysis was performed using SPSS software (version 3.1.9.7). The normality of the data distribution was assessed using both the Shapiro-Wilk and Kolmogorov-Smirnov tests. All variables were normally distributed ($P > 0.05$), justifying the use of parametric tests. Descriptive statistics including the mean, standard deviation, median, minimum, and maximum values were calculated for all experimental groups at the coronal, middle, and apical thirds of the root canal. These values provided a clear quantitative profile of the residual sealer in each region, allowing for precise comparisons across

interventions. Paired sample t-tests were conducted to assess intra-group and inter-group differences between the control group and each of the tested groups (Ultrasonic, Er,Cr:YSGG laser with 700 µs pulse duration) at each canal third. One-way ANOVA followed by post-hoc tests (LSD and Dunnett's tests) was used to determine statistically significant differences between groups. The LSD test assigned significance letters (A, B, C) to indicate homogeneous subsets, while Dunnett's test compared each experimental group with the control group. A p-value ≤ 0.05 was considered statistically significant. All data were expressed as mean ± standard deviation (SD).

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

Coronal third	G 1 Control	G2 Ultrasonic	G3 laser 700 us
N	7	7	7
Mean±SD	B	B	A
	2.43±0.54	2.43±0.78	0.57±0.78

P value 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	G 1 Control	G2 Ultrasonic	G3 laser 700 us
N	7	7	7
Mean±SD	B	B	A
	2.14±0.96	2.57±0.78	0.7±0.75

P value 0.001

LSD test was used to calculate the significant differences between the tested mean, the letters (A , 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 3. Residual filler material's mean and standard deviation (SD) for each group in the apical third of the root canal.

Apical third	G 1 Control	G2 Ultrasonic	G3 laser 700 us
N	7	7	7
Mean±SD	B	B	A
	2.43±0.78	2.85±0.37	0.86±1.46

P value 0.001

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

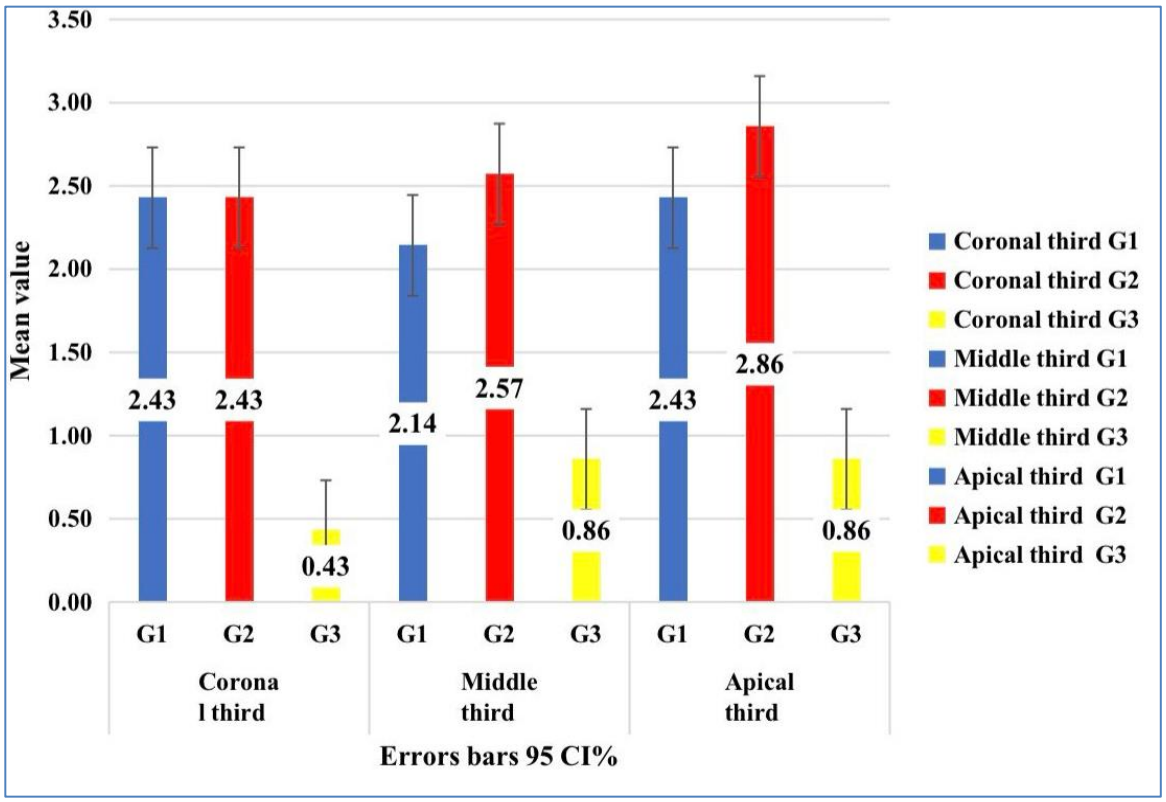


Figure 2: Bar chart represents the mean values of sealer remnants in the coronal, middle, and apical thirds for the three groups.

3. Result and discussion

Scanning Electron Microscope (SEM) Analysis:
Representative SEM images for the coronal, middle, and apical thirds are shown in figure 1, demonstrating varying amounts of residual filling material among the groups.
In group 1 (control), all three thirds of the root canal continuously showed a thick smear layer and a sizable amount of sealer residue. With residual material covering estimated to be over 80% and cleaned tubules in several areas falling below 35%, the apical third was most damaged, with the majority of dentinal tubules appearing entirely blocked. In the middle and coronal thirds, similar circumstances were noted, including restricted tubule exposure and enduring debris coatings. These results are consistent with Table 1, higher mean values for the remaining material.

In group 2 (ultrasonic activation), moderate improvement in canal cleanliness was observed. The coronal third showed the best outcome, with SEM images and ImageJ analysis indicating approximately 85% of the dentinal tubules were open. The middle third had a moderate smear layer and cleaner surfaces, with an estimated 65% of tubules being patent. However, the apical third remained problematic, where fewer than 50% of the tubules were open and thick layers of sealer residue persisted. The cleaning efficacy in this area, based on the SEM images and confirmed by table 2, was relatively low—around 10%.

Group 3 (laser activation via PIPS) continuously attained the greatest level of cleanliness. SEM pictures showed extensive tubular openness and canal walls in the coronal third that were almost completely clear of material. There were several open dentinal tubules and little remains in the middle third. Notably, more than 50–75% of the tubules were revealed in the apical third, despite the fact that some filling remains were still discernible. This indicates that even in the most difficult area of the root

canal system, there is a superior cleaning impact. The effectiveness of laser-activated irrigation is confirmed by the much lower mean values of residual material reported in table 3 ($P < 0.05$), which statistically support these results.

The SEM images and quantitative analyses (tables 1-3) taken together show that laser-activated irrigation using the PIPS technique performs better than both ultrasonic activation and conventional irrigation, especially when it comes to opening dentinal tubules in the apical region and eliminating root-filling remnants.

Quantitative Analysis:
As illustrated in Figure 2 and detailed in Tables 1–3, the mean values of residual filling material differed significantly among groups and across canal thirds.

1. Coronal third (table 1):

Ultrasonic (G2): 2.43 ± 0.78
Control (G1): 2.43 ± 0.54
Laser (G3): 0.57 ± 0.78
P value: <0.001
There was a statistically significant reduction in residue in the laser group compared to both control and ultrasonic groups.

2. Middle third (table 2):

Ultrasonic (G2): 2.57 ± 0.78
Control (G1): 2.14 ± 0.96
Laser (G3): 0.70 ± 0.75
P value: <0.001
The laser group again demonstrated the lowest residue, with statistically significant differences from both other groups.

2. Apical third (table 3):

Ultrasonic (G2): 2.85 ± 0.37
Control (G1): 2.43 ± 0.78
Laser (G3): 0.86 ± 1.46
P value: <0.001
A significant reduction in debris was observed in the laser group, indicating its enhanced cleaning effect even in the apical third.

These findings support the superior efficacy of Er,Cr:YSGG laser-activated irrigation (PIPS) compared to conventional and ultrasonic methods, particularly in reducing residual filling material across all thirds of the canal. Endodontic retreatment is often necessary in cases of persistent periapical pathology, inadequate debridement, or complex root canal anatomy that compromises the initial outcome [22]. Numerous studies have investigated the success rates of retreatment, suggesting that outcomes can be comparable to primary treatment when appropriate protocols are followed [28]. One of the primary challenges in retreatment is the complete removal of previous root canal filling materials, particularly bioceramic sealers, due to their high adhesion and potential for deep dentinal tubule penetration [29, 30].
In the present study, the ability of Er,Cr:YSGG laser-activated irrigation using PIPS technology was assessed in comparison to passive ultrasonic irrigation and conventional methods for removing bioceramic sealer remnants. Direct visual assessment under SEM was employed, which has been established as a reliable approach to evaluate canal cleanliness [31]

Our results demonstrated statistically significant differences among the three groups in all root levels (p=0.001). Laser-activated irrigation (Group 3) exhibited significantly lower residual filling material than both ultrasonic (Group 2) and the control group (Group 1), particularly in the middle and apical thirds. For example, in the apical third, the laser group recorded a mean residue of 0.86 ± 1.46, compared to 2.85 ± 0.37 in the ultrasonic group and 2.43 ± 0.78 in the control. These differences suggest that PIPS significantly enhances removal efficiency in deeper and more anatomically complex areas

Similar findings were reported by Yang et al. [23], who showed that neither ultrasonic nor laser activation alone was sufficient to completely eliminate iRoot SP and gutta-percha, though laser-based methods showed superior effectiveness. This supports our findings, which indicate that while complete removal remains challenging, laser-activated irrigation using PIPS achieves significantly cleaner canal walls.

The enhanced performance of PIPS may be attributed to its unique mechanism of action. Unlike conventional irrigation, PIPS employs low-energy, long-pulse laser bursts that generate secondary cavitation effects through rapid vapor bubble formation and collapse. These micro-explosions facilitate deep penetration of irrigants and disrupt the smear layer and debris [33, 34]. Galler et al. [35] demonstrated that laser-activated irrigants reach deeper into dentinal tubules than conventional or ultrasonic methods, especially in the apical third where accessibility is most limited. SEM analysis in this study confirmed these outcomes. In Group 3, the dentinal tubules appeared significantly cleaner across all thirds, with the apical and middle thirds showing open tubules and minimal residual debris. This is in contrast to the control and ultrasonic groups, where smear layer and filling remnants were more abundant, particularly in the apical third, where access is most difficult.

Interestingly, some samples in the laser group showed unexpected accumulation of debris in the coronal third, while the apical third appeared cleaner. This counterintuitive result may be explained by the physical dynamics of bubble propagation and fluid motion during PIPS activation. As described by Swimberghe et al. [36] and Gregorčič et al. [37], the primary vapor bubble generated within the pulp chamber expands coronally, and its collapse may induce a reverse flow of debris from the apical region to the coronal. Therefore, the accumulation observed in the coronal third may not be due to insufficient cleaning but rather to the backflow of loosened debris from deeper regions.

Another possible explanation is that the coronal third, being more accessible and already cleaned mechanically, may not have contained significant residue to begin with, and what was observed post-activation might be the redeposited material transported during irrigation. Regarding the irrigant protocol, the use of 2.5% NaOCl combined with 17% EDTA further enhanced cleaning effectiveness. Saquy et al. [38] and Zehnder [39] reported that EDTA remains effective in demineralizing dentin even in the presence of NaOCl, and this combination facilitates smear layer removal and exposes dentinal tubules for deeper irrigant penetration. This synergy is maximized by the activation from PIPS. The laser parameters used in this study (1 W, 5 Hz, 700 µs pulse duration, 1% air and water) were carefully selected to optimize activation without inducing thermal damage. The long pulse duration and low energy minimize carbonization risks while allowing sufficient energy transfer to the irrigant.

In comparison to the control group (G1) and the ultrasonic group (G2), the Er,Cr:YSGG laser group (G3) with a 700 µs pulse duration showed significantly reduced residual sealer values in the coronal, middle, and apical thirds [$p < 0.05$]. In the coronal and middle thirds, there were no discernible differences between the control and ultrasonic groups [$p > 0.05$]; however, the laser group continuously performed better than both. Due to the extended pulse duration's improved photoacoustic streaming and cavitation effects, it appears that laser-activated irrigation was more successful in penetrating and cleaning the canal walls. Deeper irrigant penetration and more effective destruction of residual materials are encouraged by these effects. Notably, the laser group also displayed noticeably fewer sealer remains in the apical third, which is usually the hardest region to clean, underscoring the effectiveness of this technology over traditional approaches. 2.5% sodium hypochlorite (NaOCl) was chosen as the irrigant concentration in this investigation because it has a well-established balance between acceptable cytotoxicity and efficient organic tissue breakdown. Even though larger concentrations (like 5.25%) have been used in earlier research, there is evidence that raising the concentration of NaOCl does not necessarily improve its

effectiveness, rather, it may raise the risk of dentinal erosion and periapical tissue irritation [39]. As a result, the chosen concentration supports the current movement to maximize safety without sacrificing cleaning capacity. Moreover, the irrigant concentration was the same for all groups in this study, so it wasn't a factor affecting comparisons across groups.

In light of the current study's findings, the efficacy of removing bioceramic sealer remnants using the PIPS technique supported by Er,Cr:YSGG laser aligns well with several recent systematic reviews. These reviews have highlighted the superiority of laser-activated irrigation in enhancing the penetration of irrigants into hard-to-reach areas of the root canal and in opening dentinal tubules compared to conventional methods such as ultrasonic activation, as reported by Badami et al. [34] and Galler et al. [35]. Such findings reinforce the potential of the PIPS technique as a promising option in endodontic retreatment, particularly when bioceramic sealers are involved. However, some studies report variations in effectiveness depending on irrigant concentration and application protocol, which may explain the observed differences in sealer removal efficacy between the coronal and apical thirds in our study. Therefore, further clinical investigations are recommended to validate the safety and effectiveness of this approach before widespread clinical adoption.

In summary, the findings of this study reinforce the effectiveness of laser-activated irrigation using the Er,Cr:YSGG laser with PIPS in endodontic retreatment. This method demonstrated superior removal of bioceramic sealer remnants compared to ultrasonic and conventional methods, particularly in the apical and middle thirds. While complete removal remains a challenge, the significant reduction in residual material and improved dentinal tubule cleanliness observed in the laser group highlight its potential as a valuable adjunct to traditional retreatment protocols. These results support the integration of PIPS into clinical practice to enhance outcomes in challenging retreatment cases.

7. Conclusion

This study aimed to evaluate the effectiveness of the PIPS technique using the Er,Cr:YSGG laser in removing bioceramic sealer remnants from root canals. The results showed that laser-activated irrigation significantly improved the removal of residual filling materials when compared to both syringe irrigation and passive ultrasonic activation ($p < 0.05$). The coronal and middle thirds of the canals showed the most noticeable improvement, while the apical third showed less pronounced differences. These findings can be attributed to the enhanced fluid dynamics achieved with the PIPS technique, which allows irrigants to reach more complex areas of the canal system. While the outcomes are encouraging and align with previous studies that support laser-assisted irrigation, it's important to note that this was an in vitro investigation. Therefore, clinical conditions such as anatomical variations and the presence of vital tissue were not simulated. Further clinical research is needed to confirm the safety and effectiveness of this approach in real-life settings. In conclusion, PIPS activation with Er,Cr:YSGG appears to be a promising adjunct for improving root canal cleanliness and could potentially be integrated into clinical practice, provided future in vivo studies validate its benefits and safety for routine use.

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ازالة بقايا مادة البايوسيراميك سيلر باستخدام إشعاع ليزرEr,Cr:YSGG بتقنية PIPS في دراسة مختبرية

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الخلاصة : هدفت هذه الدراسة المختبرية إلى تقييم فعالية استخدام الري المنشَّط بأشعة ليزر Er,Cr:YSGG في إزالة بقايا حشوات القناة الجذرية أثناء إعادة المعالجة اللبّية. اعتمدت التقنية على مبدأ التدفق الضوئي الصوتي المحفَّز بالفوتون (PIPS) باستخدام مدة نبضة تبلغ 700 ميكروثانية لتنشيط محلول هيبوكلورايت الصوديوم بتركيز 2.5% (NaOCl) ومحلول EDTA بتركيز 17%.
شملت الدراسة واحدًا وعشرين سنًا دائمًا مستأصلاً من الضواحك العلوية والسفلية أحادية الجذر. تم تنظيف القنوات وتشكيلها ثم حشوها باستخدام الجاتا بيركا وسيلر بيوسيراميكي. بعد ذلك، أُجريت إعادة المعالجة باستخدام ملفات النيكل-تيتانيوم الدوّارة (XP-endo Retreatment)، ثم قُسِّمت الأسنان عشوائيًا إلى ثلاث مجموعات (7 عينات لكل مجموعة) وفقًا لطريقة الري المستخدمة:
المجموعة الأولى: الري التقليدي بالحقنة (المجموعة الضابطة).
المجموعة الثانية: الري بالأمواج فوق الصوتية الساكنة.
المجموعة الثالثة: الري المنشَّط بالليزر باستخدام جهاز Er,Cr:YSGG بطول موجي 2780 نانومتر، مدة نبضة 700 ميكروثانية، تردد 5 هرتز، طاقة 1 واط، باستخدام رأس RFT2 وبدون رذاذ هواء أو ماء.

تم شطر العينات طوليًا وفحصها باستخدام المجهر الإلكتروني الماسح (SEM) لتقييم كمية بقايا الحشوات المتبقية في الثلث التاجي، الأوسط، والقِمي من القناة الجذرية. تم تقييم النظافة من قبل اثنين من أخصائيي علاج الجذور المعايرين باستخدام نظام تقييم مكون من أربع درجات. وقد أُجري التحليل الإحصائي باستخدام اختبار ANOVA وتحليل Tukey للمقارنات البعدية، مع تحديد مستوى الدلالة عند ($\alpha = 0.05$).

أظهرت النتائج وجود فروق ذات دلالة إحصائية بين المجموعات ($P < 0.05$)، حيث سجّلت المجموعة الثالثة انخفاضًا ملحوظًا في كمية البقايا المتبقية مقارنةً بالمجموعتين الأولى والثانية، في جميع مستويات القناة. بينما لم تُسجل فروق معنوية بين المجموعتين الأولى والثانية ($P > 0.05$)، مما يشير إلى محدودية فاعلية الري فوق الصوتي مقارنة بالتنشيط الليزري. كما لوحظ أن أفضل النتائج من حيث النظافة كانت في الثلث التاجي، تليها المنطقة الوسطى، ثم القِمية.

أظهر الري المنشط بالليزر باستخدام جهاز Er,Cr:YSGG مع تقنية PIPS ومدة نبضة 700 ميكروثانية، بالتزامن مع استخدام NaOCl بتركيز 2.5% وEDTA بتركيز 17%، فاعلية عالية في إزالة بقايا حشوات الجذر خلال إعادة المعالجة. وتشير هذه النتائج إلى أن استخدام هذه التقنية يمكن أن يُعد خيارًا فعالًا مساعدًا ضمن بروتوكولات إعادة المعالجة التقليدية، لما يوفره من كفاءة تنظيف محسّنة في جميع أجزاء القناة الجذرية.