10.21608/adjc.2025.399476.1862 Advanced Dental Journal
Volume 7 (2025) | Issue 4| Pages 577-594

Original Article

Comparative Efficacy of Er,Cr:YSGG Laser (2780 nm), Diode Laser (976 nm), and Ultrasonic Irrigation in Smear Layer Removal

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Submitted: 12-07-2025
Accepted: 27-08-2025

Abstract

Aim: This in vitro study compared the efficacy of Er,Cr:YSGG laser (2780 nm), diode laser (976 nm), passive ultrasonic irrigation (PUI), and conventional syringe irrigation (CSI) in removing smear layer from root canals, evaluating the influence of irrigant chemistry (NaOCl+EDTA, EDTA, NaOCl, saline) and root canal level (coronal, middle, apical). Superior smear layer removal is clinically significant as it enhances disinfection, sealer penetration, and long-term endodontic success. **Subjects and methods:** One hundred sixty single-rooted premolars were instrumented and randomly divided into four irrigation groups (n=40/group): Er,Cr:YSGG (25 mJ, 50 Hz) using radial-firing tip; diode laser (CW, 1.5 W); PUI; and CNI side-vented needle. They further subdivided by irrigant (n=10/subgroup). Irrigation was performed in four 15-second cycles. Smear layer removal was scored (1–5) via SEM by blinded evaluators. Data were analyzed using Kruskal-Wallis and Mann-Whitney tests ($p \leq 0.05$). **Results:** Er,Cr:YSGG achieved the lowest scores (optimal cleaning) across all thirds (1.2–2.7), outperforming diode laser (1.7–3.4), PUI (2.3–4.4), and CNI (2.4–4.7) ($p < 0.001$). NaOCl+EDTA was most effective ($p < 0.05$), though saline with Er,Cr:YSGG surpassed NaOCl alone. Apical thirds consistently showed poorer removal ($p < 0.001$). **Conclusion:** Diode laser activation surpassed PUI. Er,Cr:YSGG laser enhanced saline irrigant's efficacy. Among the tested protocols, Er,Cr:YSGG laser activation with NaOCl+EDTA demonstrated superior smear layer removal efficacy, especially in challenging apical regions.

Keywords: Er,Cr:YSGG laser, Diode laser, Laser activated irrigation, Radial firing tip, Smear layer removal.

Introduction

The complete removal of microbes, necrotic pulp tissue, and inorganic fragments from the root canal system is essential for the success of root canal therapy **(Peters et al., 2020; Abognah & Azzuz, 2022)**. However, absolute root canal debridement using traditional methods is significantly hampered by the intricate anatomy of root canals, which includes isthmuses, lateral canals, and apical deltas **(Abognah & Azzuz, 2022; Putranto & Usman, 2017)**.

On the other hand, dentinal walls and dentinal tubules of main root canals are always occluded by the smear layer, a 1-5 µm thick layer of organic and inorganic depositions created during instrumentation. It may harbour pathogens, hinder the penetration of irrigants and sealers and, jeopardize the root canal fillings' three-dimensional sealability. Therefore, for the best decontamination and obturation material adhesion, efficient smear layer removal is essential. Currently, the most effective technique for removing the smear layer is root canal irrigation procedure **(Abognah & Azzuz, 2022)**.

Despite its widespread usage, conventional syringe irrigation (CSI) technique using open-ended needles is limited in its ability to penetrate the intricate root canal spaces because of vapor lock effects and inadequate fluid dynamics **(Zou et al., 2014)**.

Consequently, side-vented irrigation needles were introduced because of its ability to induce deeper and more defined irrigant delivery, which improves the efficacy of conventional syringe needle (CSN) irrigation technique **(Boutsioukis & Arias-Moliz, 2022)**. Side-vented endodontic needles can spread fluid laterally, lowering apical pressure and enhancing debridement in the middle and coronal thirds, in contrast to open-ended endodontic needles that only release irrigant at the tip. Nevertheless, their efficacy in removing the smear layer particularly from the apical third is still restricted and less competent than the endodontic active irrigation methods **(Boutsioukis & Arias-Moliz, 2022)**. Advanced irrigation activation methods, such as, manual dynamic activation (MDA), sonic irrigation (SI), passive ultrasonic irrigation (PUI), and laser activation techniques have been studied in order to get around these problems **(Gomes et al., 2023)**.

The powerful cleansing capability of ultrasonic energy through the production of acoustic streaming and cavitation advocates using of passive ultrasonic irrigation (PUI) technique for improve irrigant penetration and debris removal **(Tonini et al., 2022)**. Despite the role of PUI cavitation in clinical situations is still controversial, various in-vitro studies demonstrated effectiveness of PUI in eliminating smear layers, especially in the apical third, where conventional syringe irrigation frequently falls short **(Tonini et al., 2022)**. But, they also reported if PUI is administered incorrectly, it may cause tip breakage **(Boutsioukis & Arias-Moliz, 2022)** or dentinal microcracks **(Limantoro et al., 2024)**.

Recently, optical activation of root canal irrigation can be a viable substitute of sonic/ultrasonic stimulation. Dental lasers can be employed for disinfection of dry & wet root canals. Direct irradiation of root canal dentin with laser beam may accompany with unwanted ablation and thermal damage **(Olivi, 2013; Olivi & Olivi, 2016)**. Exposure of root canal irrigants to laser energy enhances their fluid dynamics, penetration capability, disinfection potency & cleansing effect which produce deeper root canal sealer penetration, and better circumferential sealing and adaption to root canal dentin walls **(Abognah & Azzuz, 2022; Abdelgawad et al., 2022 a; Abdelgawad et al., 2022 b)**.

The conventional LAI initially recruited mid-infrared (MIR) lasers before transitioning to chopped near-infrared (NIR) lasers **(Olivi, 2013; Olivi & Olivi, 2016; George & Walsh, 2017)**. These lasers are transmitted through optical fiber and tips, which can be inserted to almost the full working length of root canal permitting more apical agitation of root canal irrigant **(Olivi & DiVito, 2016; Olivi & Olivi, 2016; George & Walsh, 2017; Meire & De Moor, 2024)**. Although the wavelengths of NIR—such as 810, 940, and 980-nm diode lasers—are predominantly absorbed by pigmented chromophores rather than water molecules, numerous in vitro studies confirm that the chopped diode laser energy absorbed by root canal irrigants during LAI is sufficient to induce effective fluid agitation **(Hmud et al., 2010; Olivi & Olivi, 2016; Al-Mafrachi et al., 2018)**. Moreover, other studies found that applying of CW IR lasers beam during LAI can raise the temperature of root canal irrigant, thereby increasing their kinetic movement within the root canal. In addition, fluid movement of root canal solution could be positively affected by the helical movement of laser tip required during delivery of CW IR laser energy within the canal. In short, the key interaction mechanism between NIR lasers (CW and pulsed) and root canal irrigant is photothermic **(Hmud et al., 2010; Olivi, 2013; Otero et al., 2023)**.

While prior dental research focused on 810–980 nm diodes, the newer 976-nm wavelength's higher water absorption may enhance photothermal effects, offering potential advantages in irrigant activation. This inclusion addresses a gap in literature and provides insights into wavelength-specific efficacy.

In contrast to NIR lasers, the principal mechanism of MIR laser-root canal irrigant interaction is photomechanical, even if it is initiated by the thermal effect of laser photons. The strong absorption of mid-infrared (MIR) radiation (e.g., Erbium family lasers) by water molecules in the irrigant synchronically with the conversion of light energy into thermal cause rapid transient superheating. This leads to the formation of an expandable vapor bubble, followed by subsequent photomechanical effects including, cavitation, acoustic and shock wave generation **(Olivi & DiVito, 2016; George & Walsh, 2017; De Moor et al., 2018)**. The conventional LAI using microsecond-pulsed 2.78-μm Erbium, Chromium-doped Yttrium Scandium Gallium Garnet laser (Er,Cr:YSGG) and 2.94-μm Erbium-doped Yttrium Aluminum Garnet laser (Er:YAG) lasers have traditionally relied on end-firing tips. **(Olivi & DiVito, 2016; George & Walsh, 2017; De Moor et al., 2018)**. Nevertheless, the design of these tips restricts uniform irradiation of the entire dentin surface within the root canal system, leading to suboptimal disinfection and debris removal. To address this limitation, radial-firing tips (RFT) were developed, enabling divergent laser beam delivery for broader coverage of the root canal walls. This innovation boosts fluid agitation, smear layer eradication, and overall efficacy of activated irrigation solutions **(Blanken & Verdaasdonk, 2007; George et al., 2008; Abduljalil & Kalender, 2020)**.

Hence, this study was carried out to compared four root canal irrigation techniques for smear layer removal: a pulsed athermal MIR Er,Cr:YSGG laser (2.78 μm) delivered via RFT a CW thermal NIR gallium aluminum arsenide (AlGaAs), diode laser (0.976 μm)), PUI, and CSI with a side-vented needle. The efficacy of these techniques was evaluated using different solutions: 5.25% NaOCl + 17% EDTA, 17% EDTA alone, 5.25% NaOCl alone, and saline.

Subjects and Methods

Sample Selection and Preparation

The study protocol received ethical approval from the institutional review board (approval no. NILES-EC-CU 23/9/21 [in]). A total of 160 teeth were included, divided into four experimental groups. The sample size was determined using G*Power software (v3.1.9.7, Heinrich-Heine Universität, Germany) with an effect size of 0.4, an alpha error probability of 0.05, and an actual power exceeding 0.94.

The study used freshly extracted mandibular first premolars from patients aged 18–25 years undergoing orthodontic treatment (Iandolo et al., 2023). Inclusion criteria required teeth to be intact, single-rooted, with an oval-shaped single canal, a mature apex, and minimal root curvature (<20°) **(Abdelgawad et al., 2022 a; Abdelgawad et al., 2022 b; Iandolo et al., 2023; Abaza & Harhash, 2024; Abaza et al., 2025)**. Following extraction, external debris was removed using an ultrasonic scaler and tap water **(Abaza & Harhash, 2024; Abaza et al., 2025)**. Teeth were stored in normal saline **(Abaza & Harhash, 2024)** at +4°C, and used within five days **(Iandolo et al., 2023; Abaza et al., 2025)**.

Digital radiographs in buccolingual and mesiodistal views revealed the standardized cross-section of the root canal and confirmed there was no radicular morphological anomalies calcifications, cracks, fractures, or resorptive lesions **(Abdelgawad et al., 2022 a; Abdelgawad et al., 2022 b; Abaza & Harhash, 2024)**. A low-speed diamond saw (Isomet 4000, Buehler Ltd., USA) was used to decoronate the teeth horizontally under water cooling, standardizing root length to 17 mm **(Swathi et al., 2024)**. Canal patency was verified utilizing a #10 K-file (Dentsply Sirona, Switzerland) **(Abdelgawad et al., 2022 a; Abdelgawad et al., 2022 b; Abaza & Harhash, 2024) (Abaza et al., 2025)**. Working length was ascertained by subtracting 0.5 mm from the length at which the file tip became visible at the apical foramen **(Jafarzadeh et al., 2017; Abdelgawad et al., 2022 a; Abdelgawad et al., 2022 b; Abaza & Harhash, 2024; Abaza et al., 2025)**. The root apices were externally sealed with sticky wax to preclude irrigant extrusion and simulate real clinical conditions **(Ballal et al., 2021; Iandolo et al., 2023; Abaza et al., 2025)**. Canal preparation was implemented using ProTaper Next® rotary files (Dentsply Maillefer, USA) with an endodontic motor (X-Smart, Dentsply Maillefer, USA) at 300 rpm and 2 N/m torque **(Abdelgawad et al., 2022 a; Abdelgawad et al., 2022 b; Abaza & Harhash, 2024; Abaza et al., 2025)**. After each instrumentation, canals were rinsed with 2 mL of distilled water **(Abdelgawad et al., 2022 a; Abdelgawad et al., 2022 b; Abaza et al., 2025)**.

Final Irrigation Protocols

Specimens were randomly assigned to four groups (n=40 each) based on irrigation activation technique: Er,Cr:YSGG (group I) , diode (group II) laser-activated, PUI (group III), and CSI (group IV). Each group was further subdivided into four subgroups (n=10 per subgroup) based on irrigant solution: 5.25% NaOCl + 17% EDTA (subgroup I), 17% EDTA (subgroup II), 5.25% NaOCl (subgroup III), and Normal saline (subgroup IV) (see Table 1).

• Group I (Er,Cr:YSGG laser activation): The root canal solution was activated by 2.78-µm, Er,Cr:YSGG laser (iplus, Waterlase, Biolase Technology, Irvine, CA, USA). using a 415 µm-diameter, a 21 mm-length RFT (Waterlase laser tip RF3-21, Biolase Technology, Irvine, CA, USA). The laser beam was operated at 25 mJ pulse energy, 60 µs pulse width, and 50 Hz pulse frequency **(Abdelgawad et al., 2022 a; Abaza & Harhash, 2024)**.

• Group II (Diode laser activation): The root canal solution was activated by 0.976 µm, AlGaAs diode laser (LX 16 Plus Dental Diode Laser, Guilin Woodpecker Medical Instrument Co. Ltd., China) using a 400 µm-diameter fiber optic tip (MF4-9, Guilin Woodpecker Medical Instrument Co. Ltd., China) in CW at 1.5 W power output.

Before Er,Cr:YSGG (group I) and diode (group II) lasers activation, the laser tips were positioned inside the root canal 2 mm short of the apex. To ensure accurate positioning, a rubber stopper was employed to determine the working length of the laser fiber. During activation, the laser tips were moved apico-coronally in a helical path at a rate of 1 mm per second **(Parirokh et al., 2007; Abdelgawad et al., 2022 a; Abaza & Harhash, 2024; Kaur et al., 2024)**.

• Group III (PUI): The root canal solution was activated by ultrasonic (U) tip #20/02 (Ultra X Silver, Eighteeth, Changzhou, China) connected with wireless ultrasonic device (Ultra X, Eighteeth, Changzhou, China) at 45 kHz. During activation, this flexible tip was positioned inside the root canal 1 mm short of the apex **(Monteiro et al., 2023; Silvia et al., 2023)**.

• Group IV (CSI): The root canal solution was passively delivered within root canal using a 30-gauge side-vented needle (Monoject, Sherwood Medical, Switzerland) reaching up to 1 mm short of the working length, with no activation performed **(Abdelgawad et al., 2022 b)**.

Table (1): Experimental Groups & Subgroups

Group	Activation Method	Subgroups (Irrigants)
I	Er,Cr:YSGG (2780 nm)	NaOCl+EDTA, EDTA, NaOCl, Saline
II	Diode Laser (976 nm)	NaOCl+EDTA, EDTA, NaOCl, Saline
III	PUI	NaOCl+EDTA, EDTA, NaOCl, Saline
IV	CSI (side-vented needle)	NaOCl+EDTA, EDTA, NaOCl, Saline

For activated groups (groups I-III), activation performed with four 15-second cycles (5-second intervals), totaling 60 seconds of agitation. The activation procedure was synchronized with the application of irrigant, starting and ending concurrently. The conventional group (group IV) received irrigation in corresponding cycles (4 cycles) for an equivalent duration (15 second/cycle).

Root canals of all subgroups except subgroup I, were subjected to 6 mL of single solution applied in 4 cycles (1.5 mL per cycle), while root canal of subgroup 1 received sequential irrigation (total volume of the solutions = 6 mL), 3 mL NaOCl in 2 cycle (1.5 mL per cycle) followed by 3 mL EDTA in 2 cycle (1.5 mL per cycle), separated by 2-mL distilled water rinsing.

SEM Analysis

After irrigation, canals were rinsed with 2 mL of distilled water and dried with #X4 absorbent paper points (ProTaper® Next, Dentsply, Sirona, Ballaigues, Switzerland). Gutta-percha size #X4

(ProTaper® Next, Dentsply Sirona, Ballaigues, Switzerland) was temporarily placed in the canal for guiding the groove preparation, preventing canal perforation and, avoiding of contamination from cutting debris during root splitting **(Abdelgawad et al., 2022 a; Abdelgawad et al., 2022 b; Abaza & Harhash, 2024; Abaza et al., 2025)**. Then, grooves were prepared along the whole buccal and lingual surfaces of each root, parallel to its long axes, without penetrating the root canal space. The two attached root halves were separated using gentle application of a stainless-steel chisel **(Abaza & Harhash, 2024; Abaza et al., 2025)**. One root half the was selected to be examined using an environmental scanning electron microscope (ESEM) (FEI Quanta 250 FEG, Berlin, Germany) at 2000× magnification with an electron accelerating voltage of 20 kV **(Abdelgawad et al., 2022 a; Abdelgawad et al., 2022 b; Abaza & Harhash, 2024; Abaza et al., 2025)**. Smear layer removal from coronal, middle, and apical thirds were blindly assessed by two independent, well-trained examiners (**Abdelgawad et al., 2022 a); Abdelgawad et al., 2022 b; Abaza & Harhash, 2024; Abaza et al., 2025)** in accordance to Hülsmann et al. score, a five-point scoring system **(Hülsmann et al., 1997)**. The criteria of this system was as follows (see Figure 1):

- Score 1: Full dentinal tubules visibility without smear layer.
- Score 2: Partial tubule visibility with minor smear layer.
- Score 3: Most dentinal tubules are obscured with moderate smear layer.
- Score 4: All dentinal tubules are obscured with homogeneous smear layer covering the entire canal surface.
- Score 5: All dentinal tubules are obscured with heterogeneous, heavy, irregular smear layer covering the entire canal surface.

Two experienced calibrated examiners independently evaluated the FSEM captures **(Abdelgawad et al., 2022 a; Abdelgawad et al., 2022 b)**.

Statistical Analysis

The ESEM image data were analyzed using SPSS (Statistical Package for the Social Sciences, version 25.0.0, IBM, Armonk, NY, USA). Inter- and intra-examiner reliability were confirmed using Cohen's kappa coefficient. Normality testing via the Kolmogorov-Smirnov and Shapiro-Wilk tests revealed a non-normal distribution of the data. Therefore, nonparametric tests were employed. The Kruskal-Wallis test was used for overall intergroup comparisons (based on root canal irrigant type and root third). While, the Mann-Whitney U test was applied for pairwise comparisons. A p-value of 0.05 or less was considered statistically significant.

Results

I. Comparison of Irrigation Techniques

Significant differences in smear layer removal effectiveness were noticed among the four examined groups, regardless of the irrigant used or root segment studied ($p < 0.001$). The Er,Cr:YSGG laser-activated technique (Group I) exhibited consistent superiority over alternative methods, generating the lowest smear layer scores throughout all root segments, independent of the irrigant employed (see Tables 2–4, Figures 2). Diode laser-activated irrigation technique (Groups II) performed significantly better than PUI (III) and CSI (Group IV). PUI (Group III) demonstrated significantly better smear layer removal efficacy compared to CSI (Group IV) when NaOCl+EDTA was employed in the coronal segment and when saline was utilized in the middle segment (see Tables 2–4, Figures 2).

2. Comparison of Root Canal Solutions

When comparing irrigants using the same irrigation protocol, the NaOCl+EDTA combination (Subgroup I) achieved highest smear layer removal, outperforming all other irrigant across all root segment, following EDTA alone (Subgroup II). NaOCl alone (Subgroup III) presented consistently inferior smear layer removal compared to saline (Subgroup VI) across all root segments under the same irrigation protocol—except when using the Er,Cr:YSGG laser-activated technique (Group I). In Group I, saline (Subgroup

VI) exhibited better efficacy than NaOCl alone (Subgroup III) (see Tables 2–4, Figures 3).

3. Root Segment Influence

Smear layer removal effectiveness displayed a consistent spatial pattern: cervical thirds showed the best cleaning (lowest scores), middle thirds exhibited moderate results, and apical thirds consistently demonstrated the poorest removal (highest scores) across all study groups (see Tables 2–4, Figures 2 and 3).

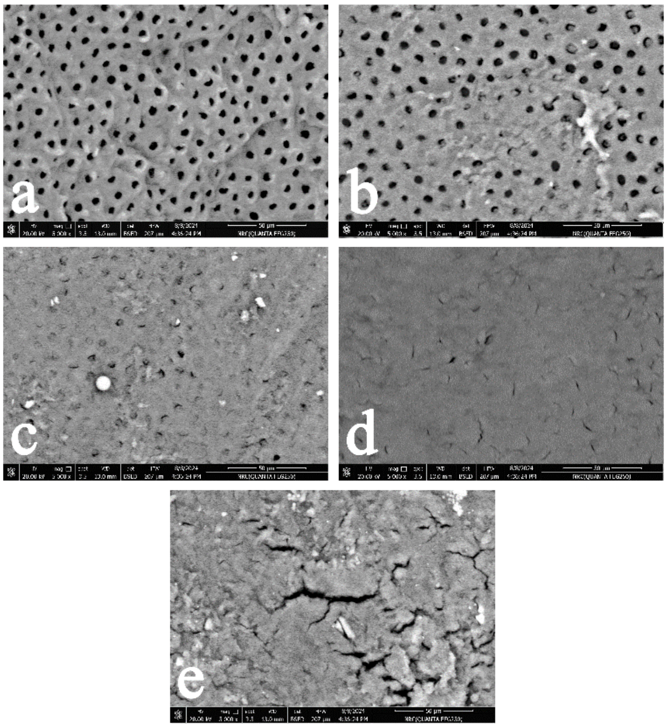

Figure 1: Representative SEM images categorized by a 5-point scoring scale: (a) Score 1: No smear layer; all dentinal tubules visible, (b) Score 2: Slight smear layer; some tubules visible , (c) Score 3: Homogenous smear layer hiding the major dentin surface, a few dentinal tubules visible, (d) Score 4: Homogeneous smear layer hiding the entire dentin surface, no tubules visible, (e) Score 5: Heavy heterogeneous smear layer hiding the dentin surface.

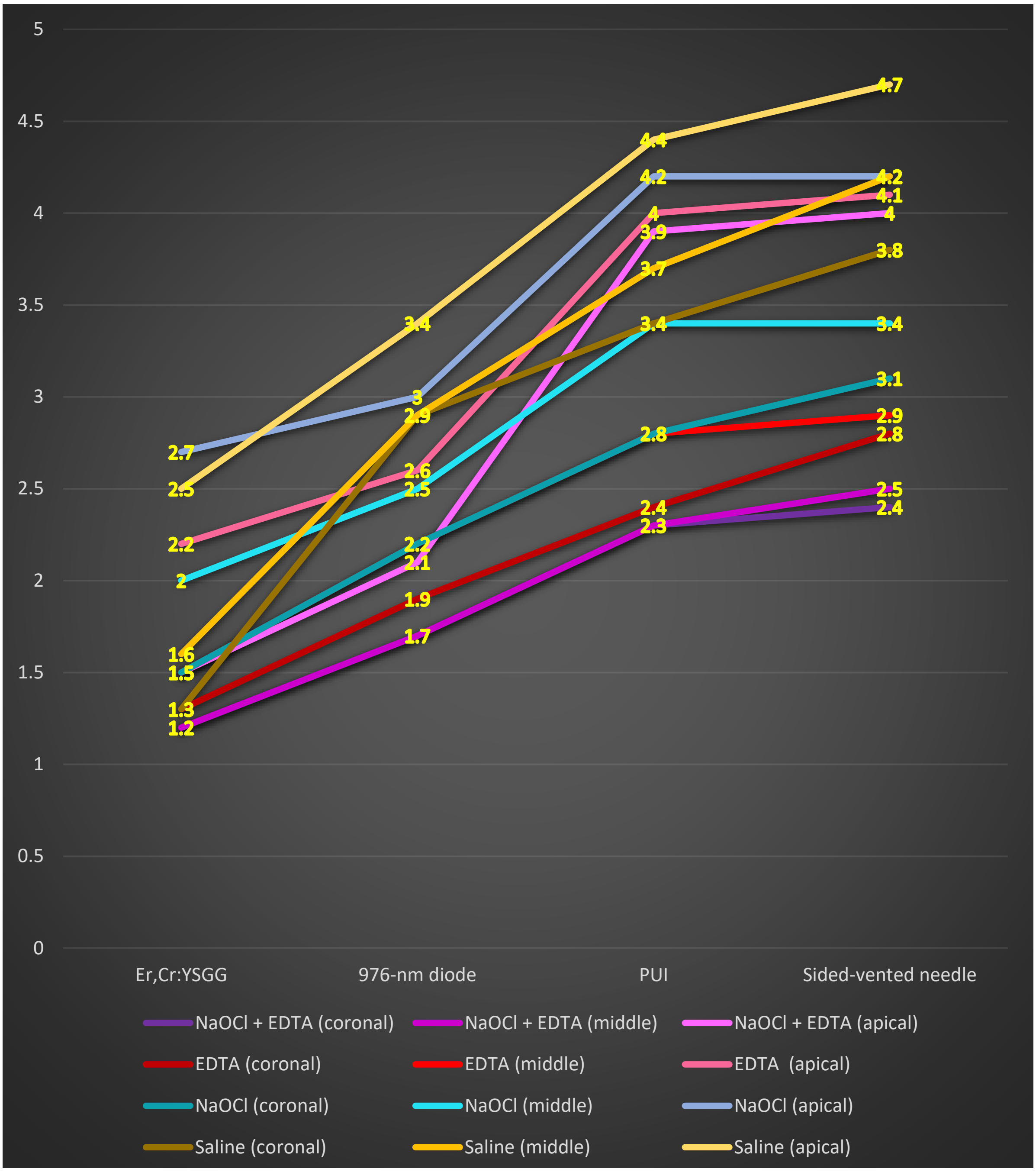

Figure 2: The mean of smear layer scores of all groups recorded at different root thirds

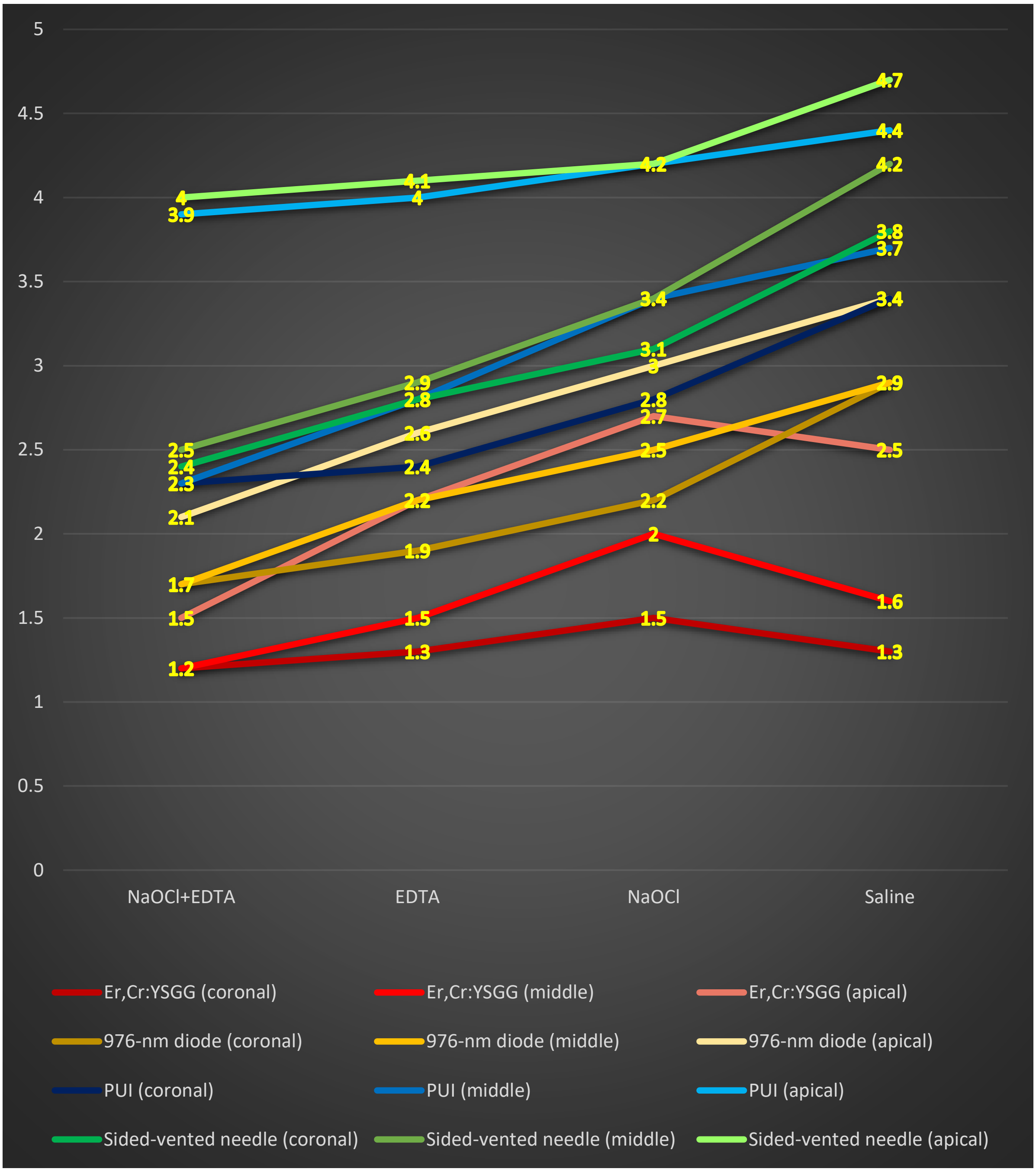

Figure 3: The mean of smear layer scores of all subgroups recorded at different root thirds

Table (2): Mean, standard deviation (SD), and the statistical comparisons of smear layer scores in coronal third between the examined groups & subgroups

	NaOCl +EDTA	EDTA (17%)	NaOCl (5.25%)	Saline	*Kruskal-Wallis H*	*P-value*
Er,Cr:YSGG	1.2±0.422 A, a	1.3±0.483 A, a	1.5±0.527 A, a	1.3±0.483 A, a	2.1111	0.550
976-nm diode	1.7±483 B, a	1.9±0.316 B, ab	2.2±0.422 B, b	2.9±0.316 B, c	24.648	<0.001*
PUI	2.3±0.483 C, a	2.4±0.516 C, ab	2.8±0.422 C, b	3.4±0.516 C, c	17.549	0.001*
CSI	2.4±0.516 D, a	2.8±0.422 C, ab	3.1±0.316 C, b	3.8±0.422 C, c	24.190	<0.001*
Kruskal-Wallis H	22.063	24.967	27.965	30.752		
P-value	<0.001*	<0.001*	<0.001*	<0.001*		

- (*) Values had statistically significant difference at (P < 0.05).
- Different lowercase letters (a, b, c, d, e) indicate significant differences within each row (P < 0.05).
- Different uppercase letters (A, B, C) indicate significant differences within each column (P < 0.05).

Table (3): Mean, standard deviation (SD), and the statistical comparisons of smear layer scores in middle third between the examined groups & subgroups

	NaOCl+EDTA	EDTA (17%)	NaOCl (5.25%)	Saline	*Kruskal-Wallis H*	*P-value*
Er,Cr:YSGG	1.2±0.422 A, a	1.5±0.527 A, a	2±0 A, b	1.6±0.516 A, a	13.066	0.004*
976-nm diode	1.7±0.483 B, a	2.2±0.422 B, b	2.5±0.527 B, bc	2.9±0.316 B, c	20.382	<0.001*
PUI	2.3±0.483 C, a	2.8±0.422 C, b	3.4±0.516 C, c	3.7±0.483 C, c	22.870	<0.001*
CSI	2.5±0.527 C, a	2.9±0.316 C, a	3.4±0.516 C, b	4.2±0.422 D, c	28.026	<0.001*
Kruskal-Wallis H	22.063	25.458	27.215	33.781		
P-value	<0.001*	<0.001*	<0.001*	<0.001*		

- (*) Values had statistically significant difference at (P < 0.05).
- Different lowercase letters (a, b, c, d, e) indicate significant differences within each row (P < 0.05).
- Different uppercase letters (A, B, C) indicate significant differences within each column (P < 0.05).

Table (4): Mean, standard deviation (SD), and the statistical comparisons of smear layer scores in apical third between the examined groups & subgroups

	NaOCl+EDTA	EDTA	NaOCl (5.25%)	Saline	*Kruskal-Wallis H*	*P-value*
Er,Cr:YSGG	1.5±0.527 A, a	2.2±0.422 A, a	2.7±0.483 A, a	2.5±0.527 A, a	18.068	<0.001*
976-nm diode	2.1±0.316 B, a	2.6±0.516 A, ab	3±0. A, b	3.4±0.516 B, c	24.778	<0.001*
PUI	3.9±0.316 C, a	4±0 B, a	4.2±0.422 B, ab	4.4±0.516 C, b	9.066	0.028*
CSI	4±0 C, a	4.1±0.316 B, ab	4.2±0.422 B, b	4.7±0.483 C, c	15.080	0.002*
Kruskal-Wallis H	35.702	24.823	34.482	29.852		
P-value	<0.001*	<0.001*	<0.001*	<0.001*		

- (*) Values had statistically significant difference at (P < 0.05).
- Different lowercase letters (a, b, c, d, e) indicate significant differences within each row (P < 0.05).
- Different uppercase letters (A, B, C) indicate significant differences within each column (P < 0.05).

Discussion

The complete elimination of organic and inorganic debris from root canal walls stands as a fundamental requirement for achieving predictable endodontic outcomes **(Jhajharia et al., 2015)**. Contemporary research identifies three primary determinants of irrigation success: the delivery methodology, agitation approach, and solution chemistry **(Olivi & Olivi, 2016; Jhajharia et al., 2015; Dioguardi et al., 2018; Cheung et al., 2021; Abdelgawad et al., 2022 a; Abdelgawad et al., 2022 b; Abaza & Harhash, 2024; Bao et al., 2024)**. Among modern agitation technologies, ultrasonic & laser-induced activation systems have gained recognition for their ability to potentiate irrigant activity and optimize dentinal surface debridement **(Olivi, 2013; Olivi & Olivi, 2016; Olivi & DiVito, 2016; George & Walsh, 2017; De Moor et al., 2018; Tonini et al., 2022; Gomes et al., 2023; Otero et al., 2023)**, though performance outcomes remain closely tied to operational parameters and solution characteristics **(Olivi, 2013; Olivi & Olivi, 2016; Olivi & DiVito, 2016; George & Walsh, 2017; De Moor et al., 2018; Otero et al., 2023)**.

This study conducted a systematic comparison of four distinct irrigation protocols employing different chemical formulations: sodium hypochlorite with EDTA combination therapy, EDTA alone, sodium hypochlorite monotherapy, and physiological saline as a negative control. The evaluation encompassed conventional needle irrigation (CNI) using side-vented needles along with three activation techniques: (1) Er,Cr:YSGG laser (2780 nm) with conical RFT tip, (2) a novel 976-nm diode laser with plain tip, and (3) passive ultrasonic irrigation (PUI). Notably, this investigation represents, to our knowledge, the first comprehensive head-to-head comparison of 976-nm diode laser-activated irrigation, 2780-nm Er,Cr:YSGG laser-activated irrigation, and PUI for smear layer removal efficacy. The assessment was performed across all root canal regions (coronal, middle, and apical thirds) using multiple irrigation protocols, providing a complete evaluation of each technique's cleaning effectiveness under standardized conditions.

The experimental data unequivocally revealed that Er,Cr:YSGG laser activation with radial firing tips (RFT) outperformed all other tested irrigation modalities. This technique produced markedly superior dentinal cleanliness relative to diode laser activation, passive ultrasonic irrigation, and conventional needle irrigation, maintaining its advantage across all tested chemical solutions and root canal levels.

The efficacy of laser-assisted irrigation demonstrated in this study corroborates existing literature, with numerous investigations confirming its exceptional debridement capabilities **(Sabari, 2012; Wang et al., 2017; Montero-Miralles et al., 2018; Aksoy et al., 2019; Jameel & Zakarial., 2020; Al-baker & Al-Huwaizi, 2021; Rasheed & Jawad, 2021; Abdelgawad et al., 2022 a; Abaza & Harhash, 2024)**. The Er,Cr:YSGG system's exceptional performance appears attributable to its unique capacity to induce vigorous fluid dynamics through two primary mechanisms; intense transient cavitation phenomena and robust shock wave and acoustic streaming effects. These synergistic actions facilitate both deeper irrigant penetration into dentinal structures and more complete elimination of organic/inorganic residues **(Sabari, 2012; Wang et al., 2017; Montero-Miralles et al., 2018; Aksoy et al., 2019; Jameel & Zakarial., 2020; Al-baker & Al-Huwaizi, 2021; Rasheed & Jawad, 2021; Abdelgawad et al., 2022 a; Abaza & Harhash, 2024)**.

These observations are consistent with prior research documenting improved cleaning outcomes with methodologies of photomechanical influences of Er,Cr:YSGG laser, further validating the clinical potential of laser-assisted endodontic irrigation **(Blanken & Verdaasdonk, 2007; George et al., 2008; Sabari, 2012; Olivi & DiVito, 2016; George & Walsh, 2017; Wang et al., 2017; De Moor et al., 2018; Montero-Miralles et al., 2018; Aksoy et al., 2019; Abduljalil & Kalender, 2020; Jameel & Zakarial., 2020; Al-baker & Al-Huwaizi, 2021; Rasheed & Jawad, 2021; Abdelgawad et al., 2022 a; Abdelgawad et al., 2022 a; Abaza & Harhash, 2024)**. For example, studies of **(George et al., 2008; Sabari, 2012; Montero-Miralles et al., 2018; Al-baker & Al-Huwaizi, 2021; Rasheed & Jawad, 2021; Jameel & Zakarial., 2020; Abaza & Harhash, 2024)** found that Er,Cr:YSGG-laser irradiation is significantly enhanced the cleaning effectiveness of different chemical irrigants such as, peroxide, ethylenediaminetetraacetic acid -Cetavlon (EDTAC), water, normal saline, 2% chlorohexidine (CHX), and 17% EDTA, and 3% and 5.25% NaOCl compared to non-activated irrigation. Notably, even alternative natural irrigants like Salvadora persica and saline demonstrated improved efficacy when activated by Er,Cr:YSGG laser, as documented by **(Abdelgawad et al., 2022 a)**. Moreover, **(Al-Farawn et al., 2019)** and **(Varghese et al., 2025)** reported superior smear layer removal when 17% EDTA or 5.25% NaOCl was laser-activated with Er,Cr:YSGG laser in comparison to diode lasers; 940 nm & 808 nm, respectively.

Although not as effective as micro-pulsed Er,Cr:YSGG technology, 976-nm diode laser-activated irrigation still exhibited significant advantages over conventional needle irrigation in all root canal regions and with all irrigants tested. CW 976-nm diode laser enhanced smear layer removal compared to both PUI and non-activated controls (CSI with side-vented needle). This improvement is likely due to the photothermal effects of laser irradiation, which boost irrigant agitation through improving kinetics and hydrodynamic activity of irrigating solutions and augmenting the chelating action of EDTA, and the tissue-dissolving capacity of NaOCl **(Ramirez-San-Juan et al., 2010; Olivi & DiVito, 2016; De Moor et al., 2018; Tonini et al., 2022; Schoppink et al., 2023)**. As well, CW diode laser irradiation may generating vapor bubbles within the exposed solution and inducing subsequent photomechanical waves that further increase cleaning efficiency of root canal irrigant **(Ramirez-San-Juan et al., 2010; Schoppink et al., 2023)**.

These results align with previous studies confirming that diode laser-activated irrigation surpasses conventional techniques **(Nabi & Farooq, 2020; Raza et al., 2020; Barakat, 2021; Elkhodary & Morsy, 2023; (Salam et al., 2024)**.

Furthermore, the use of CW 976-nm diode laser significantly increased the efficacy of the tested irrigants in eliminating the smear layer compared to PUI. This finding align with earlier SEM studies, which confirmed that diode laser-activated irrigation removes the smear layer more effectively than ultrasonic activation **(Abraham et al., 2019; Raza et al., 2020;**

Karunakar et al., 2021). However, contrary to some studies that reported PUI is similar or superior smear layer removal capability compared to diode laser activation **(Ekim & Erdemir, 2015; Al-baker & Al-Huwaizi, 2021; Vineetha et al., 2022; Elkhodary & Morsy, 2023; Kaur et al., 2024)**, the discrepancy may stem from variations in experimental protocols. Factors such as activation time, application technique (e.g., tip positioning), number of activations, laser wavelength, beam parameters (power/pulse settings), and optical delivery systems could account for these differences **(Ekim & Erdemir, 2015; Abraham et al., 2019; Raza et al., 2020; Al-baker & Al-Huwaizi, 2021; Karunakar et al., 2021; Vineetha et al., 2022; Elkhodary & Morsy, 2023)**.

Additionally, PUI performed better in smear layer removal than CSI with side-vented needle. Prior research confirms similar results supporting PUI's enhanced efficacy over syringe irrigation technique (Ekim & Erdemir, 2015) (Al-baker & Al-Huwaizi, 2021) (Vineetha et al., 2022) (Elkhodary & Morsy, 2023) (Kaur et al., 2024). This may be ascribed to the mechanism of action of the acoustic energy transmitted from the oscillating U-file to the root canal solution, generating fluid cavitation and acoustic streaming. As a result, PUI effectively dislodges debris and enhances the irrigant's smear layer removal capability. Also, the reflux action induced during PUI promotes coronal displacement of debris **(Ekim & Erdemir, 2015; Abraham et al., 2019; Raza et al., 2020; Karunakar et al., 2021; Vineetha et al., 2022)**.

Comparative SEM analysis of irrigants under identical irrigation protocols revealed that the NaOCl+EDTA combination showed greater smear layer elimination, achieving the highest efficacy across all root segments, followed by 17% EDTA. 5.25% NaOCl consistently underperformed compared to saline in all root regions when CSI, PUI, diode laser-activated irrigation techniques used. The superior smear layer removal efficacy of the NaOCl-EDTA combination stems from their complementary chemical actions: EDTA effectively dissolves the inorganic components, while NaOCl targets the organic matter within the radicular smear layer. When used individually, each solution demonstrates limited effectiveness, as EDTA alone only removes inorganic constituents and NaOCl solely addresses organic components. In contrast, normal saline lacks any chemical reactivity with smear layer elements, rendering it incapable of meaningful smear layer elimination. These results are supported by previous studies that have documented similar patterns of irrigant effectiveness **(Menezes et al., 2003; Faria et al., 2011; Murugesan et al., 2013; Kandil et al., 2014; Sanabria-Liviac et al., 2017; Wang et al., 2017; Iandolo et al., 2023; Tong et al., 2023)**.

Interestingly, when Er,Cr:YSGG laser activation was employed, normal saline demonstrated superior smear layer removal efficacy compared to 5.25% NaOCl solution. This counterintuitive finding suggests that saline has greater affinity to Er,Cr:YSGG than that of NaOCl, leading to much more mechanical activation including cavitation, shock and acoustic wave generations dislodging more smear layer away from root canal dentin.

This counterintuitive finding suggests that normal saline exhibits significantly greater interaction efficiency with Er,Cr:YSGG laser energy compared to 5.25% NaOCl. The enhanced affinity results in more vigorous mechanical activation effects, including; intensive cavitation bubble formation, stronger shockwave propagation, and more pronounced acoustic streaming. These amplified physical phenomena collectively produce superior mechanical debridement, effectively dislodging and removing smear layer deposits from root canal dentin surfaces. The differential response may be accredited to saline's optimal viscosity for Er,Cr:YSGG laser energy transfer, NaOCl's potential attenuation of Er,Cr:YSGG-laser effects due to its chemical composition, or better photon absorption characteristics in saline leading to more efficient photoacoustic conversion. This surprising finding corroborate previous research demonstrating similar differential effectiveness among saline and NaOCl when used with Er,Cr:YSGG laser activation **(Abdelgawad et al., 2022 a; Abaza & Harhash, 2024)**.

The assessment of smear layer removal also revealed a distinct regional pattern, with cleaning efficacy decreasing progressively from coronal to apical regions. The highest smear layer scores (indicating poorest removal) were consistently observed in apical dentin, followed by intermediate values in middle thirds, while coronal sections demonstrated the most effective debridement (lowest scores). This gradient suggests that the cleaning effectiveness of activated (laser and ultrasonic) and non-activated irrigation techniques diminishes significantly in apical regions. Several anatomical factors likely contribute to this phenomenon as the complex morphology of apical root anatomy, and the frequent presence of sclerotic dentin with reduced tubular permeability, a condition that typically progresses with age **(Rasheed & Jawad, 2021) (Montero-Miralles et al., 2018)**. These findings align with numerous previous investigations that have evaluated the performance of Er,Cr:YSGG and diode laser-activated, PUI, and CSI irrigation techniques across different root levels **(Wang et al., 2017; Montero-Miralles et al., 2018; Aksoy et al., 2019; Nabi & Farooq, 2020; Abdelgawad et al., 2022 a; Abaza & Harhash, 2024; Salam et al., 2024)**.

This in vitro study has several limitations that should be noted. The first limitation is the lack of quantitative data on bacterial elimination. ESEM provides visual evidence of smear layer removal but does not quantify bacterial reduction. A clean dentinal surface (observed via SEM) does not necessarily mean complete bacterial eradication, which is critical for endodontic success. The second limitation is related to two-dimensional imaging of ESEM captures. In fact, ESEM produces static, 2D images of selected areas, which may not represent the entire root canal system. Dentin tubules and complex anatomy may not be fully assessed, leading to potential false interpretations of irrigation efficacy. Additional limitations include no functional or biological assessment were made during this study such as, antimicrobial efficacy of the irrigant was not evaluated, changes of radicular dentin permeability, surface characteristics, and potassium and calcium ions after irrigant application were not assessed, and root surface temperature during laser activation was not measured.

Future research should be conducted with advanced imaging techniques. (i.e. using confocal laser scanning microscopy (CLSM) – To assess 3D biofilm penetration and bacterial viability after LAI, micro-CT scans – To evaluate irrigant penetration in complex root canal anatomy, and atomic force microscopy (AFM) – To analyze nanoscale surface changes in dentin after laser activation. Comparative in-vitro studies utilizing standardized biofilm models (e.g., Enterococcus faecalis, multispecies biofilms) to compare antibacterial efficacy of LAI and CSI are recommended. Also, randomized controlled trials (RCTs) comparing LAI and CSI in healing rates and post-treatment infections are needed to assess long-term outcomes of both techniques.

Conclusion

Within the limitations of this in vitro study, the results revealed that Er,Cr:YSGG laser-activated irrigation outperformed both 976 nm diode laser activation and conventional needle irrigation in smear layer removal across all root canal levels when using identical irrigants. 976-nm diode laser activation significantly enhanced smear layer removal compared to PUI and CNI. The synergistic combination of NaOCl and EDTA further improved debridement effectiveness, regardless of the activation method. Saline with Er,Cr:YSGG activation surprisingly removed more smear layer than NaOCl alone, suggesting a strong mechanical (rather than chemical) cleaning effect.

Conflict of Interest:

The authors declare no conflict of interest.

Funding:
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Ethics:
This study protocol was approved by the Scientific Research Ethics Committee of National Institute of Laser Enhanced Sciences (NILES), Cairo University- on: 21/9/2023 approval number NILES-EC-CU 23/9/21 [in].

Data Availability:
Data will be available upon request.

CRediT statement:
Author 1: Data curation, Writing - review & editing, Writing - original draft, Methodology, Conceptualization, Resources.

Author 2: Data curation, Conceptualization, Project administration, Supervision, Methodology, Writing - review & editing, Writing - original draft.

Author 3: Methodology, Writing - original draft, Writing - review & editing, Investigation, Formal analysis, Supervision, Data curation.

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