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Effect of Er:YAG Laser-Activated Irrigation with Side-Firing Spiral Endo Tip on Dentin Mineral Composition of Tooth Root Canals

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Abstract: Background: Treating tooth root canal systems with Er:YAG laser together with irrigants has been shown to be effective in reducing biofilms formed by *Enterococcus faecalis*. This study investigated whether laser-activated irrigation (LAI) with side-firing Endo tip (LiteTouch™; Light Instruments, Yokneam, Israel) affects dentin mineral composition when used with common endodontic irrigants. Methods: Root canals of extracted human teeth were treated with Er:YAG laser using a side-firing Endo tip combined with 17% ethylenediaminetetraacetic acid (EDTA) and/or 2.5% NaOCl in continuous or intermittent mode for 60 s. Dentin mineral composition (Ca, P, O) in coronal, middle, and apical regions of root canals was examined by energy dispersive X-ray spectroscopy. Results: The use of LAI with continuous EDTA resulted in the largest reduction in Ca and P levels. A final NaOCl rinse mitigated the EDTA-mediated mineral loss in all root canal regions and increased the O content. Likewise, the reduced Ca/O and Ca/P ratios caused by continuous EDTA irrigation were reversed when combined with a final NaOCl rinse. Conclusions: LAI with Er:YAG Endo tip using continuous EDTA irrigation followed by NaOCl caused minimal dentin mineral loss and can therefore be considered to be a safe treatment module for cleaning root canals.

Keywords: Er:YAG laser-activated irrigation; dentin minerals; irrigation solution; endodontics; root canals

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1. Introduction

Successful root canal treatment depends on effective shaping, cleaning, and filling of the root canal system. A significant challenge in endodontic procedures is removing the smear layer and biofilm from root canal walls [1]. Due to the anatomical complexity of root canals, mechanical cleaning procedures may fail to reach all intra-canal spaces, leaving behind microbial residues [2] that can penetrate deeply into dentinal tubules and initiate infection [3].

While conventional mechanical procedures remove bacteria, they often cannot eliminate deep-seated microbes [4]. Various rinsing solutions are commonly used to achieve a greater effect on biofilm within the root canal [5]. Sodium hypochlorite (NaOCl) remains the gold standard due to its potent antibacterial properties [6,7]. However, the small amount of irrigation and application time cannot allow the irrigation solution to penetrate deeply into various tooth spaces and side channels. The volume solution that remains within the root canal is often insufficient to fully eliminate microbial residue [8,9].

To improve outcomes, combined treatments using NaOCl with chelating agents such as ethylenediaminetetraacetic acid (EDTA) have been tested [10–12]. NaOCl is recommended as a final rinse after EDTA [13,14] or as part of an alternating irrigation protocol, which has shown greater efficiency than NaOCl alone [15–17].

Laser-activated irrigation (LAI) has emerged as a promising technique to enhance the effectiveness of irrigation solutions [18]. The erbium-doped yttrium aluminum garnet (Er:YAG) laser, with a wavelength of 2940 nm, is absorbed by water molecules, resulting in efficient expansion, vaporization, and micro-explosions [19]. Er:YAG LAI has been shown to open dentinal tubules by eliminating the smear layer [20–22] and contribute to the removal of bacterial biofilms [23–25].

This study aimed to investigate the effect of Er:YAG LAI using the LiteTouch side-firing spiral Endo tip on the mineral content of dentin at the surface of different root canal regions when applied with common irrigation solutions. Understanding these effects is crucial for optimizing endodontic treatments and ensuring long-term success of root canal procedures. The null hypothesis was that there would be no significant difference in the mineral content of dentin at the surface of different root canal regions when treated with Er:YAG laser-activated irrigation using a side-firing spiral Endo tip.

2. Materials and Methods

2.1. Tooth Preparation

Fifty-four root canals of extracted human teeth (Helsinki approval number 040617-HMO) were standardized using distal roots of lower molars. The length from coronal to apical was standardized to 18 mm by using a straight handpiece with a disc. X-ray images were captured for each tooth to verify the accuracy of the working length. Roots were prepared for coronal flaring using No. 2 and 3 gates Glidden drills followed by a size 10 k-type file, until the apical foramen became visible. Size 15 k-type and a 20 k-type files were used, along with ProTaper (Dentsply Maillefer, Baillaigues, Switzerland) rotary files to X3 were used. Finally, a size 35 k-type file and a size 40 k-type file were used to achieve effective chemo-mechanical cleaning. After each file, the canals were irrigated with 10 mL of double-distilled water (DDW) using a 25-gauge needle with a length of 16 mm (0.5 × 16 mm), which was inserted into the root canal, leaving 2 mm outside the root canal. A size 10 k-type file was used to maintain patency. A total of 324 sample data points were analyzed in the course of this study.

2.2. Laser Specifications

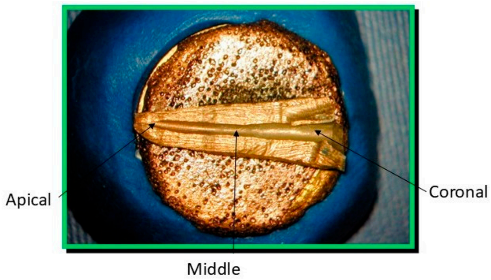
An Er:YAG laser (Light Instruments, Yokneam, Israel) with side-firing spiral Endo tip (LiteTouch™; Light Instruments, Yokneam, Israel) was used. The circumferential spiral slit of the Endo tip is flexible, hollow, conical, and round in cross-section [25]. Power output was set to 1.5 W, with 150 mJ energy and 10 Hz frequency, applied for 60 s. The working method involved moving the tip up and down 1–2 mm at a time in the coronal-apical direction, with the following irrigation regimes:

- Group A: No treatment (control).
- Group B: Exposed simultaneously to Er:YAG laser–Endo tip and irrigation with 10 mL of 17% EDTA solution for 60 s.
- Group C: Exposed simultaneously to Er:YAG laser–Endo tip and 4 times irrigation with 1 mL of 17% EDTA solution for 15 s each time.
- Group D: Exposed simultaneously to Er:YAG laser–Endo tip and irrigation with 10 mL of 17% EDTA solution for 60 s, followed by irrigation with 10 mL of 2.5% NaOCl solution for 60 s.
- Group E: Exposed simultaneously to Er:YAG laser–Endo tip and 4 times irrigation with 1 mL of 17% EDTA solution for 15 s each time, followed by irrigation with 10 mL of 2.5% NaOCl solution for 60 s.

- Group F: Exposed simultaneously to Er:YAG laser–Endo tip and irrigation with 10 mL of 2.5% NaOCl solution for 60 s.

The root canals were irrigated with 25-gauge endodontic needles (Navitip, Ultradent, South Jordan, UT, USA). The 2.5% NaOCl solution was prepared by diluting 6% NaOCl (Romical, Israel) in sterile DDW, and the 17% EDTA solution was obtained from Dentech (Holon, Israel). Following the different treatments, tooth samples were longitudinally processed by using a high-speed bur (40,000 rpm; Wheel Shape Diamond Burs G1 (ISO No 042-30) Derech Haifa 37, Kiryat Ata, 2822639 Israel). Thereafter, each tooth was carefully bisected along its long axis using a precision scalpel cutting instrument. This process resulted in two equal halves, providing a clear view of the internal tooth structure.

Illustration of the three tooth areas (coronal, middle, and apical) analyzed in this study:



2.3. *Microanalysis of Surface Element Distribution by Energy X-Ray Spectroscopy (EDS)*

The surface minerals of the dentin minerals were studied using an FEI Quanta 200 scanning electron microscope (SEM) equipped with EDAX EDS system (Sapphire Si[Li] ultrathin window [UTW] detector, spectral resolution 128-eV) (FEI Europe B.V., Eindhoven, The Netherlands). The analysis was performed at a spectral acquisition time of 50 s and an accelerating voltage of 15.0 kV. Quantification was performed using the EDAX-ZAF matrix correction. The distribution of key elements calcium (Ca), phosphate (P) and oxygen (O) was evaluated, and element content was determined in weight %. The data were analyzed using EDAX Genesis software and compared to the control group.

2.4. *Statistical Analysis*

Two-way ANOVA and post hoc Tukey's Honestly Significant Difference (HSD) tests were used to compare between the different treatment groups. Each subgroup consisted of 10 teeth analyzed for Ca, P, O, and Ca/O, Ca/P ratios. Results were determined to be statistically significant when the α value was less than 0.05. Data are presented as mean ± standard deviation (SD).

Statistical analysis was conducted using a two-way Analysis of Variance (ANOVA) to examine the effects of groups and their interaction dependent variable. The ANOVA model partitioned the total sum of squares (SS) into components attributable to the main effects of groups and location, their interaction, and residual error. F-statistics were calculated as the ratio of mean squares (MS) for each effect to the mean square error (MSE), with degrees of freedom (df) determined by the number of factor levels and sample size. Statistical significance was assessed using p-values.

3. Results

Surface Mineral Analysis

The root canal surface mineral levels of Ca, P, and O, as well as the Ca/O and Ca/P ratios in the dentin, following laser activation with the different irrigation solutions were determined by energy X-ray spectroscopy (EDS). Figure 1 describes the average content of all three root canal regions (coronal, middle, apical) of the six tested groups, while Figure 2 describes the mineral content by the root canal region. The results show that oxygen content was lowest in the root canals treated with laser irradiation and intermittent (15 s × 4 times)

17% EDTA irrigation, while the highest oxygen content was found in the root canals treated with laser irradiation in continuous (60 s) and intermittent EDTA treatment followed by a final 2.5% NaOCl irrigation. The lowest Ca levels were found in the root canals treated with laser irradiation and continuous EDTA irrigation (Figures 1 and 2), which was statistically significant in the coronal and middle regions, while it was insignificant in the apical region. The highest Ca levels were found in the laser irradiation with continuous (60 s) treatment with 17% EDTA followed by final irrigation with 2.5% NaOCl (Figure 1; Supplementary Table S1). This was significant in the coronal and middle regions while not significant in the apical region (Figure 2). The lowest P levels were found in the root canals treated with laser irradiation with continuous (60 s) 17% EDTA treatment, while the highest P levels were found in the root canals treated with laser irradiation with continuous 2.5% NaOCl irrigation (Figures 1 and 2; Supplementary Table S1).

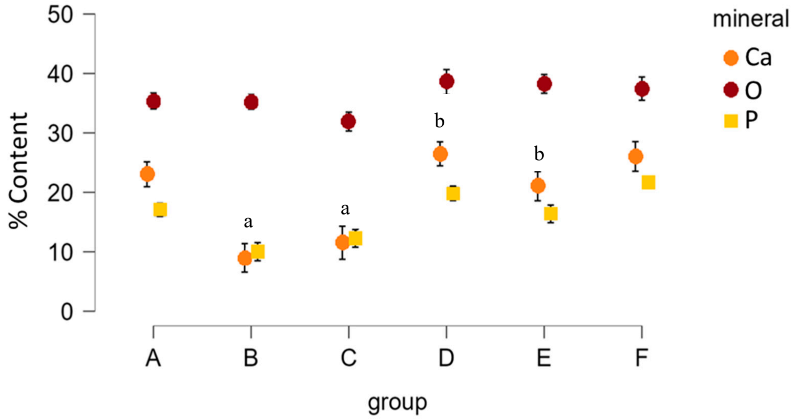


Figure 1. Mean mineral composition of the root canal surface following Er:YAG laser activation with the following irrigation methods: (A) Control; (B) Er:YAG laser with 17% EDTA continuous irrigation for 60 s; (C) Er:YAG laser with 15 s × 4 intermittent 17% EDTA irrigation; (D) Er:YAG laser with 17% EDTA continuous irrigation for 60 s followed by 2.5% NaOCl; (E) Er:YAG laser with 15 × 4 intermittent 17% EDTA irrigation followed by 2.5% NaOCl; and (F) Er:YAG laser with 60 s continuous 2.5% NaOCl irrigation. Data are average of 10 teeth in each treatment group. Ca = Calcium, O = Oxygen, P = Phosphate. a: $p < 0.001$ in comparison to control (group A). b: $p < 0.001$ in comparison to EDTA without NaOCl. Statistical significance between the different groups is presented in Table 1.

Table 1. Statistical significance in mineral composition between the different groups presented in Figure 1.

Post Hoc Comparisons of the Different Treatments for Each Mineral [a]							
Treatment Groups		**Mean Differences**	**SE**	**t**	**Cohen's d**	p_{tukey}	**Significance**
				Calcium			
A	B	14.061	1.237	11.371	2.936	<0.001	***
	C	11.523	1.237	9.318	2.406	<0.001	***
	D	−3.441	1.237	−2.783	−0.719	0.328	
	E	2.002	1.237	1.619	0.418	0.979	
	F	−3	1.636	−1.834	−0.626	0.933	
B	C	−2.538	1.237	−2.053	−0.53	0.841	
	D	−17.502	1.237	−14.15	−3.654	<0.001	***
	E	−12.059	1.237	−9.752	−2.518	<0.001	***
	F	−17.061	1.636	−10.43	−3.562	<0.001	***
C	D	−14.964	1.237	−12.1	−3.124	<0.001	***
	E	−9.521	1.237	−7.699	−1.988	<0.001	***
	F	−14.522	1.636	−8.877	−3.032	<0.001	***
D	E	5.443	1.237	4.402	1.137	0.002	**
	F	0.442	1.636	0.27	0.092	1	
E	F	−5.002	1.636	−3.057	−1.044	0.178	

Table 1. *Cont.*

Post Hoc Comparisons of the Different Treatments for Each Mineral [a]							
Treatment Groups		**Mean Differences**	**SE**	**t**	**Cohen's d**	p_{tukey}	**Significance**
				Oxygen			
A	B	0.147	1.237	0.119	0.031	1	
	C	3.47	1.237	2.806	0.724	0.313	
	D	−3.156	1.237	−2.552	−0.659	0.492	
	E	−2.879	1.237	−2.328	−0.601	0.663	
	F	−2.072	1.636	−1.267	−0.433	0.999	
B	C	3.322	1.237	2.687	0.694	0.393	
	D	−3.303	1.237	−2.671	−0.69	0.404	
	E	−3.026	1.237	−2.447	−0.632	0.572	
	F	−2.22	1.636	−1.357	−0.463	0.997	
C	D	−6.626	1.237	−5.358	−1.383	<0.001	***
	E	−6.348	1.237	−5.134	−1.326	<0.001	***
	F	−5.542	1.636	−3.388	−1.157	0.072	
D	E	0.277	1.237	0.224	0.058	1	
	F	1.084	1.636	0.662	0.226	1	
E	F	0.806	1.636	0.493	0.168	1	
				Phosphate			
A	B	7.043	1.237	5.696	1.471	<0.001	***
	C	4.808	1.237	3.888	1.004	0.014	*
	D	−2.777	1.237	−2.246	−0.58	0.722	
	E	0.679	1.237	0.549	0.142	1	
	F	−4.621	1.636	−2.825	−0.965	0.301	
B	C	−2.236	1.237	−1.808	−0.467	0.941	
	D	−9.82	1.237	−7.941	−2.05	<0.001	***
	E	−6.365	1.237	−5.147	−1.329	<0.001	***
	F	−11.664	1.636	−7.13	−2.435	<0.001	***
C	D	−7.585	1.237	−6.133	−1.584	<0.001	***
	E	−4.129	1.237	−3.339	−0.862	0.084	
	F	−9.429	1.636	−5.764	−1.969	<0.001	***
D	E	3.456	1.237	2.794	0.722	0.32	
	F	−1.844	1.636	−1.127	−0.385	1	
E	F	−5.3	1.636	−3.24	−1.107	0.111	

[a] (A) Control; (B) Er:YAG laser with 17% EDTA continuous irrigation for 60 s irrigation; (C) Er:YAG laser with 15 s × 4 intermittent 17% EDTA irrigation; (D) Er:YAG laser with 17% EDTA for continuous irrigation for 60 s followed by 2.5% NaOCl; (E) Er:YAG laser with 15 × 4 intermittent 17% EDTA irrigation followed by 2.5% NaOCl; and (F) Er:YAG laser with 60 s continuous 2.5% NaOCl irrigation. Ten teeth in each treatment group. Ca = Calcium, O = Oxygen, P = Phosphate. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

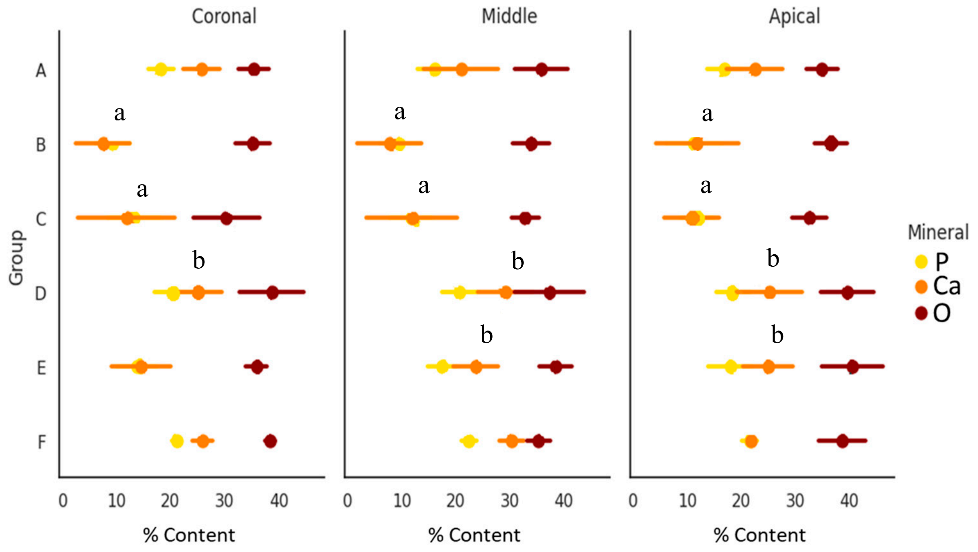


Figure 2. Mineral composition analysis of the root canal surface according to coronal, middle, and apical regions following Er:YAG laser activation with the irrigation methods: (A) Control; (B) Er:YAG laser with 17% EDTA continuous irrigation for 60 s; (C) Er:YAG laser with 15 s × 4 intermittent 17%

EDTA irrigation (D); Er:YAG laser with 17% EDTA continuous irrigation for 60 s followed by 2.5% NaOCl; (E) Er:YAG laser with 15 × 4 intermittent 17% EDTA irrigation followed by 2.5% NaOCl; and (F) Er:YAG laser with 60 s continuous 2.5% NaOCl irrigation. Data are average of 10 teeth in each treatment group. Ca = Calcium, O = Oxygen, P = Phosphate. a: $p < 0.001$ in comparison to control (group A). b: $p < 0.001$ in comparison to EDTA without NaOCl. Statistical significance is presented in Table 2 and Supplementary Tables S2–S4.

Table 2. Two-way ANOVA statistics for significant differences between treatment groups for minerals presented in Figure 2.

Cases	Sum of Squares	df	Mean Square	F	p_{tukey}	η^2
Group	8280.819	5	1656.164	72.202	<0.001	0.152
Mineral	32,810.077	2	16,405.038	715.189	<0.001	0.604
Group × Mineral	2530.629	10	253.063	11.032	<0.001	0.047
Residuals	10,735.004	468	22.938			

Note. Type III sum of squares.

The Ca/O ratios were consistently lower in the root canals treated with laser irradiation and continuous EDTA irrigation in all teeth regions (Figure 3 and Supplementary Table S5). The treatment group with highest Ca/O ratios differed between the canal regions. The highest Ca/O ratios were found in the coronal region of the control untreated group, while the highest Ca/O ratios were found in the middle region in the laser irradiation with continuous 2.5% NaOCl irrigation group (Figures 3 and 4). In the apical region, the highest Ca/O ratios were found in the laser irradiation with continuous EDTA treatment with final 2.5% NaOCl irrigation group (Figures 3 and 4 and Supplementary Table S5).

Table 3 and Supplementary Tables S2–S4 show the statistical parameters obtained from ANOVA calculations of data presented in Figure 4. There is a high significance ($p < 0.001$) between the groups. However, there were no statistically significant differences between the tooth's coronal, middle, and apical areas.

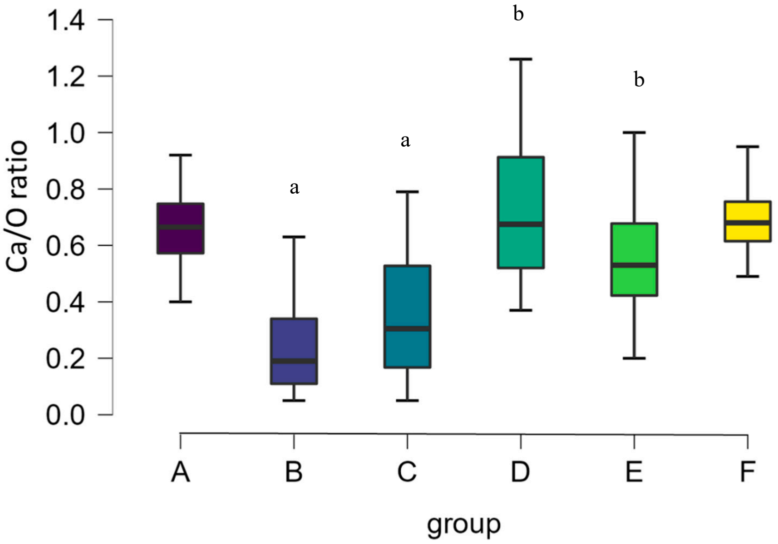


Figure 3. The Ca/O ratio in root canal surfaces following Er:YAG laser activation with the different irrigation methods: (A) Control; (B) Er:YAG laser with 17% EDTA continuous irrigation for 60 s; (C) Er:YAG laser with 15 s × 4 intermittent 17% EDTA irrigation; (D) Er:YAG laser with 17% EDTA continuous irrigation for 60 s followed by 2.5% NaOCl; (E) Er:YAG laser with 15 × 4 intermittent 17% EDTA irrigation followed by 2.5% NaOCl; and (F) Er:YAG laser with 60 s continuous 2.5% NaOCl irrigation. Data are average of 10 teeth in each treatment group. Ca = Calcium, O = Oxygen. a: $p < 0.001$ in comparison to control (group A). b: $p < 0.001$ in comparison to EDTA without NaOCl.

Table 3. Two-way ANOVA of Ca/O ratio for treatment groups and tooth area.

Cases	Sum of Squares	df	Mean Square	F	p_{tukey}
Group	5.060	5	1.012	27.661	<0.001
Area	0.118	2	0.059	1.608	0.204
Group × Area	0.795	10	0.079	2.172	0.023
Residuals	5.268	144	0.037		

Note. Type III sum of squares.

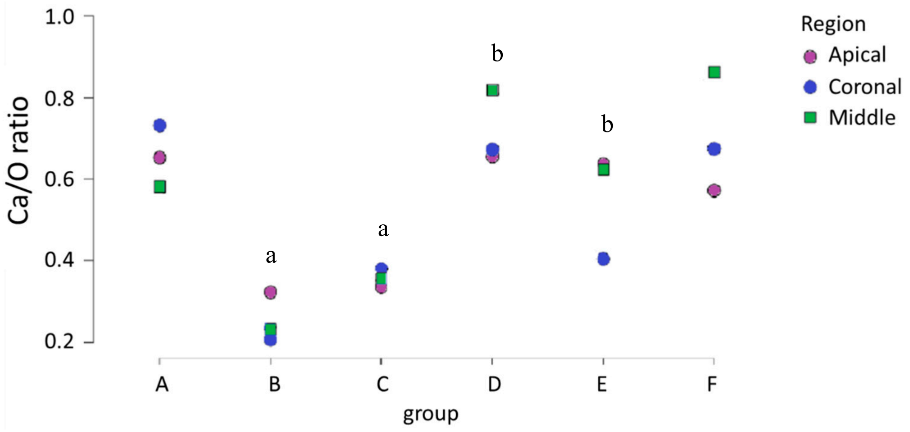


Figure 4. Changes in Ca/O in the root canal surface according to coronal, middle, and apical regions following Er:Yag laser activation with the irrigation methods: (A) Control; (B) Er:YAG laser with 17% EDTA continuous irrigation for 60 s; (C) Er:YAG laser with 15 s × 4 intermittent 17% EDTA irrigation; (D) Er:YAG laser with 17% EDTA continuous irrigation for 60 s followed by 2.5% NaOCl; (E) Er:YAG laser with 15 × 4 intermittent 17% EDTA irrigation followed by 2.5% NaOCl; and (F) Er:YAG laser with 60 s continuous 2.5% NaOCl irrigation. Data are average of 10 teeth in each treatment group. Ca = Calcium, O = Oxygen. a: $p < 0.001$ in comparison to control (group A). b: $p < 0.001$ in comparison to EDTA without NaOCl. Statistical significance is presented in Table 3.

The lowest Ca/P ratios were found in the root canals treated with laser irradiation and continuous EDTA irrigation in all teeth regions (Figures 5 and 6 and Supplementary Table S6). The treatment group with the highest Ca/P ratios differed between the canal regions. The highest Ca/P ratios were found in the control group in the coronal region and in the laser irradiation with continuous 2.5% NaOCl irrigation group in the middle region (Figures 5 and 6). In the apical region, there was no significant difference in the Ca/P ratio in the root canals treated with the laser irradiation with continuous (60 s) and intermittent EDTA treatment (Figures 5 and 6 and Supplementary Table S6).

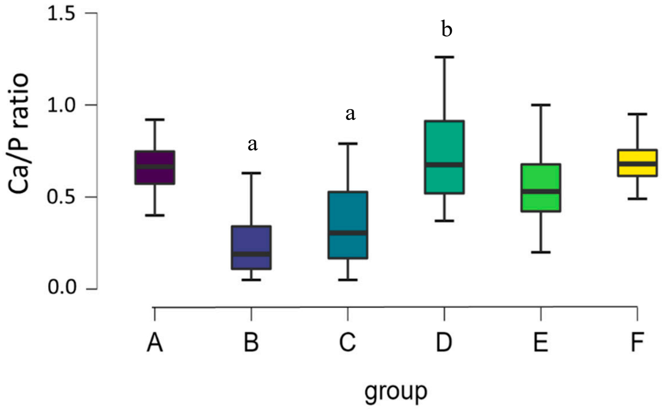


Figure 5. Changes in Ca/P in the root-canal surface following Er:YAG laser activation with the irrigation methods: (A) Control; (B) Er:YAG laser with 17% EDTA continuous irrigation for 60 s;

(C) Er:YAG laser with 15 s × 4 intermittent 17% EDTA irrigation; (D) Er:YAG laser with 17% EDTA continuous irrigation for 60 s followed by 2.5% NaOCl; (E) Er:YAG laser with 15 × 4 intermittent 17% EDTA irrigation followed by 2.5% NaOCl; and (F) Er:YAG laser with 60 s continuous 2.5% NaOCl irrigation. Data are average of 10 teeth in each treatment group. Ca = Calcium, P = Phosphate. a: $p < 0.001$ in comparison to control (group A). b: $p < 0.001$ in comparison to EDTA without NaOCl.

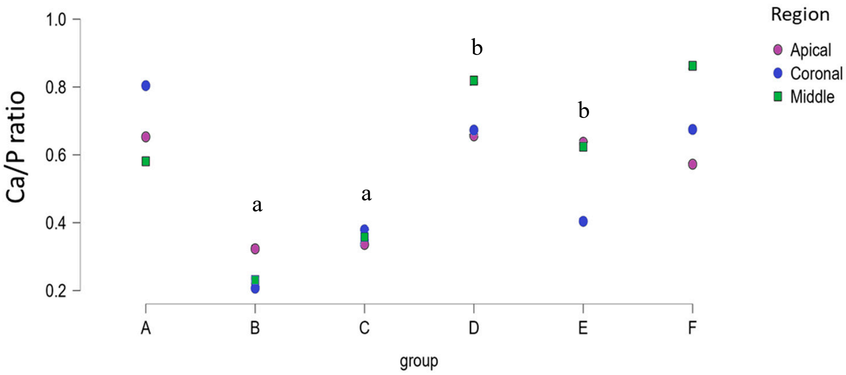


Figure 6. Changes in Ca/P in the root canal surface according to coronal, middle, and apical regions following Er:YAG laser activation with the irrigation methods: (A) Control; (B) Er:YAG laser with 17% EDTA continuous irrigation for 60 s; (C) Er:YAG laser with 15 s × 4 intermittent 17% EDTA irrigation; (D) Er:YAG laser with 17% EDTA continuous irrigation for 60 s followed by 2.5% NaOCl; (E) Er:YAG laser with 15 × 4 intermittent 17% EDTA irrigation followed by 2.5% NaOCl; and (F) Er:YAG laser with 60 s continuous 2.5% NaOCl irrigation. Ca = Calcium, P = Phosphate. a: $p < 0.001$ in comparison to control (group A). b: $p < 0.001$ in comparison to EDTA without NaOCl.

4. Discussion

Our previous studies have shown that the combination of Er:YAG laser and certain irrigants used in the endodontics effectively removes bacterial biofilms from the root canal [25]. The aim of this study was to examine the null hypothesis of minimizing chemical effects on dentin during endodontic laser treatment to maintain tooth integrity. We therefore tested the effects of different irrigant combinations with Er:YAG laser side-firing Endo tip treatment on the mineral composition of the dentin in the root canals. The mineral content of the enamel and dentin root canal walls is an important inorganic parameter for the integrity of the teeth. The study showed that different LAI protocols can significantly alter the calcium (Ca), phosphorus (P), and oxygen (O) content in the root canal surface, as well as the Ca/O and Ca/P ratios.

The observation that continuous EDTA irrigation activated by Er:YAG laser led to the lowest Ca and P levels is particularly noteworthy. While this treatment may effectively remove the smear layer, it also risks excessive demineralization. This finding goes along with previous studies that have shown strong demineralizing effect of EDTA on dentin [25]. However, data from this research showed that a final NaOCl rinse following EDTA treatment helped restore Ca and P levels closer to those of the control group. This may be due to precipitation of divalent cations by NaOCl [26]. This suggests that a carefully sequenced irrigation protocol can balance effective cleaning with the preservation of dentin structure. This observation is consistent with recent studies by Tartari et al. [27], who reported that alternating NaOCl and EDTA can minimize dentin demineralization while maintaining cleaning efficacy.

The variation in treatment effects across different root canal regions highlights the importance of considering the entire root canal length when developing irrigation protocols. The fact that some treatments showed significant effects in the coronal and middle regions but not in the apical region suggests that reaching the apical third remains challenging, even with advanced techniques like LAI. Tay et al. [28] showed that the vapor locks caused by air entrapment at the apical end of root canals hinders effective treatment. This difficulty in treating the apical third has been well-documented in previous studies [27] and remains a significant challenge in endodontics. We observed that the use of the Endo spiral-firing tip together with irrigants overcomes this obstacle [25].

Changes in Ca/O and Ca/P ratios provide further insight into structural changes occurring in the dentin following treatment. These ratios are important indicators of dentin mineralization and can affect properties such as micro-hardness and solubility [27,29]. The consistent lowering of these ratios with continuous EDTA irrigation suggests a risk of over-demineralization, while their restoration with a final NaOCl rinse supports the potential protective effect of this step. Our results are consistent with previous studies of Ballal et al. [30] who reported similar changes in dentin composition following various irrigation protocols that can alter dentin composition and surface characteristics. Our approach aimed to minimize any chemically induced damage to dentin in order to preserve its integrity by demonstrating the specific effects of Er:YAG laser activation in combination with common irrigants.

The observed variations in mineral composition and ratios depending on the irrigation protocol underscore the complexity of optimizing root canal treatments. The use of the Er:YAG laser adds a new dimension to this complexity. While laser activation has shown promise in improving the efficacy of irrigation solutions [19,23,25], there is evidence that its effects on dentin mineralization must be carefully considered. These findings have important clinical implications. While EDTA is crucial for removing the smear layer, its use should be carefully controlled, particularly when applied in combination with Er:YAG laser. The protective effect of a final NaOCl rinse highlights the importance of irrigation sequence in maintaining dentin integrity while achieving thorough cleaning. This complies with recent clinical guidelines that recommend a final rinse with NaOCl after EDTA application [31]. This study also contributes to the growing body of evidence supporting the use of laser technology in endodontics. The Er:YAG laser, in particular, has shown promising value in various endodontic applications [20,32,33].

However, it is important to acknowledge the limitations of this study. As an in vitro investigation, it may not fully replicate the complex conditions of the oral environment. Factors such as temperature, presence of organic tissue, and the dynamic nature of the oral microbiome could influence the effects of irrigation protocols in vivo [34]. Additionally, while we examined short-term changes in dentin composition, long-term effects on tooth strength and treatment outcomes remain to be explored.

Future research should focus on several key areas. First, long-term studies are needed to evaluate the effects of these treatments on dentin properties and the success rates of endodontic procedures. Second, in vivo studies are crucial to confirm these results in a clinical setting. Third, the investigation of potential synergies between laser activation and novel irrigation solutions or techniques could lead to further improvements in endodontic treatments [35,36]. Finally, the development of more precise methods to control laser energy distribution within the root canal could help to optimize treatment outcomes while minimizing undesirable effects on dentin structure [37].

5. Conclusions

Er:YAG laser-activated irrigation, when combined with EDTA followed by a final NaOCl rinse, was found to minimize mineral loss from the dentin. This protocol offers a promising approach to optimizing endodontic treatments that balances thorough cleaning with preservation of dentin structural integrity. Clinicians should consider the potential impact on dentin mineralization when selecting irrigation protocols, especially when using laser activation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/photonics11100978/s1; Supplementary Tables S1–S6. Supplementary Table S1. Percentage of average mineral content in the teeth after each treatment. Average of data from 10 teeth in each group. Supplementary Table S2. Post Hoc comparisons of oxygen (O) content between tooth areas of each treatment. Supplementary Table S3. Post Hoc comparisons and ptukey for phosphate (P) content between treatment groups and tooth areas. Supplementary

Table S4. Present Post Hoc comparisons of calcium (Ca) content between treatment group and tooth area. Supplementary Table S5. Descriptive values of Ca/O ratios after the different treatments. Supplementary Table S6. Descriptive values of Ca/P ratios after the various treatments.

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