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Evaluation of Er,Cr:YSGG laser technique for fiber post removal of endodontically treated teeth using micro-computed tomography

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Abstract

Various clinical techniques such as removal kits, ultrasonic tips, burs, and drills, have been used for fiber post removal in endodontically treated teeth. In most clinical cases, the dental practitioners prefer to use ultrasonic tips, despite the heat generation and the formation of microcracks induced in the radicular dentin. The purpose of this study was to investigate the effectiveness of using erbium, chromium: yttrium-scandium-gallium-garnet (Er,Cr:YSGG) laser (2780 nm) as an alternative fiber post removal technique and to compare it to an ultrasonic method using micro-computed tomography (micro-CT). The operating parameters of the X-ray tube were set to 50 kVp and 300 mA. This approach allowed the generation of 2D lateral projections that were then used to reconstruct the 3D volume in DICOM format. Fiber posts were removed from 20 endodontically treated single-rooted premolars ($n = 10$) using an ultrasonic vibrator with diamond-coated ultrasonic tip (control method), or Er,Cr:YSGG laser irradiation protocol; average power 2.5 W, repetition rate 20 Hz, pulse duration 140 μs, 40% air and 20% water, and close-contact mode. The number of sections with newly formed microcracks, the loss of dentinal tissue, the amount of the residual resin cement, and the removal time were evaluated for both methods. The data were analyzed using paired t-test, Wilcoxon signed-rank and Mann–Whitney U tests at level of significance $a = .05$. In the laser-treated group the parameters regarding microcracks formation (21 ± 16) and removal time (4.7 ± 1.1 min) were advantageous compared to the ultrasonic-treated group (42 ± 27 and 9.2 ± 1.0 min, respectively), indicating that Er,Cr:YSGG laser could be an alternative fiber post removal technique.

KEYWORDS
Er,Cr:YSGG laser, fiber post removal, micro-computed tomography, ultrasonic vibration

- Two post removal methods were investigated using Er,Cr:YSGG laser and ultrasonics.
- Both treatments exhibited the similar dentin volume loss and residual resin cement.
- Laser treatment presented lower formation of microcracks.
- Laser treatment removed posts in shorter time than ultrasonics.

1 | INTRODUCTION

Root canal treatment triggers critical changes in tooth biomechanics, and is associated with radicular or coronal tissue loss and lower mechanical strength of the tooth (Dietschi et al., 2008). The potential complication of compromised root structure emphasizes the importance of highly conservative restorative approaches after the completion of endodontic treatments (Carvalho et al., 2018; Corsentino et al., 2018). Nevertheless, in many clinical cases the treatment plan is necessary to include placement of posts for improving retention of the restorative material.

Fiber posts have attracted increasing attention in recent years due to their aesthetic and mechanical properties (Ahmed et al., 2017). They exhibit biomechanical behavior similar to that of dentin, and also achieve bonding to root canal system of the teeth via resin cements. As a result, the system post-cement-dentin acts as a unit and leads to a homogeneous stress distribution during mastication (da Silva et al., 2010). Root canal treatment procedures are associated with long-term tooth survival. However, microleakage and eventually bacterial recontamination may occur (Siqueira, 2001), and as a consequence fiber post removal is necessary before endodontic retreatment. Endodontic surgery could be an option, but non-surgical root canal retreatment has been claimed to be a choice that offers a more favorable long-term outcome compared to surgical treatments (Torabinejad et al., 2009). Although the bonding effectiveness of fiber posts at deeper areas of the root canals has not been sufficiently documented, the removal of a glass fiber post can be a complex and challenging procedure (Rodrigues et al., 2017).

Removal kits, ultrasonic tips, burs, and drills (Haupt et al., 2018; Purger et al., 2021), and more recently lasers (Cho et al., 2022; Deeb et al., 2019) have been used for fiber post removal. Ultrasonic tips, along with burs and drills, have been found to be relatively effective, not only in terms of removal of the post, but also in terms of resin cement removal without compromising the integrity of the adjacent tooth structure (Lindemann et al., 2005; Haupt et al., 2018). Fiber post removal kits might be a good option, as they speed up the procedure, reducing the loss of tooth structure without decreasing fracture resistance (Aydemir et al., 2018). However, in most of the cases, the dentist is unaware of the type and technical characteristics of the fiber post. Thus, the effectiveness of using a removal kit becomes doubtful because it is effective only for its own post system. In these cases, the dental clinician usually prefers ultrasonic treatment, despite the induced heat and the increased formation of microcracks along the root dentin (Altshul et al., 1997; Dominici et al., 2005; Ettrich et al., 2007).

Erbium lasers have recently been suggested as alternative technique to remove fiber posts, leaving the adjacent dentinal walls almost intact and generating relatively low heat compared to ultrasonic treatments (Cho et al., 2022; Deeb et al., 2019). More specifically, erbium lasers include erbium: yttrium-aluminum-garnet (Er:YAG), which emits at 2940 nm and erbium, chromium: yttrium-scandium-gallium-garnet (Er,Cr:YSGG), which emits at 2780 nm. Both erbium wavelengths have the advantage of very high absorption coefficients to water compared to the other laser wavelengths (1200 mm^{-1} for Er:YAG and 400 mm^{-1} for Er,Cr:YSGG) (Diaci & Gaspirc, 2012). This is a very important property when using them for interacting with aqueous substances during operation, avoiding penetration of the laser irradiation through the tooth structures (Papadopoulos et al., 2021). Furthermore, their pulsed irradiation prevents high increase in temperature at the area of application.

It has been demonstrated that the components of resin cements are vaporized by laser energy through a mechanism known as thermal ablation (Rechmann et al., 2014; Sari et al., 2014). The degradation of resin cements induced by laser energy absorption can lead to debonding and post removal (Cho et al., 2022; Deeb et al., 2019). To date, the effect of Er,Cr:YSGG laser as a fiber post removal technique has been studied only in relation to dentin volume loss and heat generation (Cho et al., 2022), but there are no data in the literature for the amount of residual resin cement in the root canals or the formation of microcracks during the procedure.

Therefore, the purpose of this in vitro study was to investigate the effectiveness of Er,Cr:YSGG laser treatment as a fiber post removal technique by evaluating the dentin volume loss, the amount of residual resin cement into the root canal, the microcrack formation, and the removal time compared to a conventional ultrasonic method, which was served as a control. Micro-computed tomography (μ-CT) was used for the purposes of this study, as it has been claimed as an accurate, sensitive and nondestructive method in the previous similar reports (Arukaslan & Aydemir, 2019; Cho et al., 2022).

Four null hypotheses were set prior to this investigation; the first null hypothesis ($H_0$1) stated that the tested post removal treatments would remove the same dentin volume during the clinical procedures. The second null hypothesis ($H_0$2) stated that the tested post removal treatments would leave the same residual resin cement bonded to the walls of the root canal after the clinical procedures. The third null hypothesis ($H_0$3) stated that the tested post removal treatments would induce the same number of microcracks during the clinical procedures. Finally, the fourth null hypothesis ($H_0$4) stated that the tested treatments would need the same time to remove the posts from the root canals.

2 | MATERIALS AND METHODS

2.1 | Preparation of the specimens

This study was conducted respecting the rules of the local Ethical and Research Committee and the policies of the Aristotle University of Thessaloniki (approval number: 8/October 30, 2019) in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments. Twenty single-rooted, freshly extracted (up to 6 weeks) premolars for periodontical or orthodontic reasons were collected and stored in 0.1% chloramine solution at 6°C until the experiment. The inclusion criteria for the teeth also included mandibular premolars with complete root development, straight roots (0–10°), similar root diameter and length (±0.5 mm), and no pre-existing endodontic treatment. The coronal part of each tooth was removed at the level of the cement-enamel junction (CEJ) using a water-cooled diamond saw (Isomet, Buehler, Lake Bluff, IL) and the root length was modified up to 13 mm. Then the root specimens were coated with a thin layer of polyether impression material and placed in acrylic resin (Technovit 4071, Heraeus, Hanau, Germany) to standardize their position during the entire experimental period.

Subsequently, the teeth were endodontically treated using rotary files (ProTaper Gold®, Dentsply Maillefer, Ballaigues, Switzerland) up to the F3 file according to the shaping and finishing sequence (S1, S2, F1, F2, and F3) following the manufacturer's instructions. The root canals were irrigated with 2.5% sodium hypochlorite (NaOCl) and distilled water, and then dried with paper points. Root canal obturation was performed using the single-cone technique with gutta-percha (ProTaper Guttapercha Points, Dentsply Maillefer, Ballaigues, Switzerland) and an epoxy resin-based sealer (AH Plus, Dentsply-DeTrey, Konstanz, Germany). The specimens were stored at 37°C and 100% humidity for 1 week to ensure the setting of the sealer. The post space was set to 8 mm in depth and 1.3 mm in diameter using drills specially designed for RelyX™ fiber posts (RelyX™ fiber post drills, 3 M ESPE, St. Paul, MN), and was confirmed with X-ray images for each specimen utilizing Xpod (MyRay, Imola, Italy) at 70 KVp and 7 mA and exposure time 0.12 s, which is recommended for premolars. A custom-made device was used to standardize the focus-to-sensor distance (35 cm) and the positions of both digital sensor and head of X-ray machine, so that central X-ray beam was directed perpendicularly to the sensor's surface.

2.2 | Fiber post cementation procedure

For the baseline measurement of the post space, the specimens were scanned using a micro-computed tomography (micro-CT) scanner (X-Cube; MOLECUBES, Ghent, Belgium) according to Swain and Xue (2009). More specifically, the specimens were dried for 2 h at room temperature (23°C) before using micro-CT to enable identification of microcracks. To maintain a steady humidity level throughout the scanning, the specimens were put in a sample holder that was tightly sealed with plastic foil. Each specimen was scanned by using an isotropic resolution of 50-μm at 50 kV and 300 mA through 360° rotation around the vertical axis, with a rotation step of 0.5°, camera exposure time of 5000 ms, and frame averaging of 1. The X-rays were filtered with a 1 mm-thick aluminum filter. This approach allowed the generation of 2D lateral projections that were then used to reconstruct the 3D volume in DICOM format. Before the cementation of the posts and in compliance with the manufacturer's instructions, the fiber posts (RelyX™, 3 M ESPE, St. Paul, MN) were cleaned with alcohol.

Then the cementation of the fiber posts was followed using a self-adhesive resin cement (RelyX™ Unicem™, 3 M ESPE, St. Paul, MN), which was injected into both the post surface and root canal. The elongation tip was immersed in the resin cement and held at this position throughout the resin cement application process to avoid trapping air in the resin cement. The post (smooth, tapered, size No1 RelyX™ fiber post, 1.3 mm diameter) was immediately inserted, slightly twisted, and moderate pressure was applied on the top to hold it in position. The excess resin cement was removed after light-cured for 2 s with a blade and the specimens were photopolymerized for 40 s utilizing a LED light-curing unit (Elipar S10, 3 M ESPE, St. Paul, MN) at 1200 mW/cm^2 with standard curing mode. A radiometer (Demetron L.E.D. Radiometer, Kerr Corp, Orange, CA) was used to verify the output irradiance of the LED unit. Radiographs confirmed proper positioning of the posts. The teeth were stored at 100% relative humidity and at 37°C for 24 h before removal.

2.3 | Post removal procedures

For the removal of the fiber posts the specimens were randomly divided into two groups ($n = 10$); the ultrasonic group (control) and the laser group. In the ultrasonic group, the fiber posts were removed using an endodontic diamond-coated ultrasonic tip (ET18D 76 μm, 18 mm length, taper 5%, Satelec; Acteon Group, Norwich, UK) with an ultrasonic vibration generator (P5 Newtron, Satelec; Acteon Group, Norwich, UK) under water-cooling and medium/high-power settings. In the laser group, the fiber posts were removed using an Er,Cr:YSGG laser (Biolase® Technology, Irvine, CA) emitting at 2780 nm with a Waterlase MD gold handpiece and MZ5 endodontic tip (diameter 500 μm, length 9 mm, Biolase® Technology, Irvine, CA). The laser settings were as follows: average power 2.5 W, repetition rate 20 Hz, pulse duration 140 μs, 40% air and 20% water, and close-contact mode (1 mm from the fiber post) (Cho et al., 2022). The power density was 318.47 W/cm^2 and the energy density was 9554.1 J/cm^2 for each attempt of post removal (30 s of irradiation). The laser tip was operated in parallel to the fiber post circumferentially to concentrate the light energy perpendicular to the cementation area. To ensure the highest efficiency, every ultrasonic or laser tip was replaced with a new one, in every specimen. After each 30 s of ultrasonic or laser

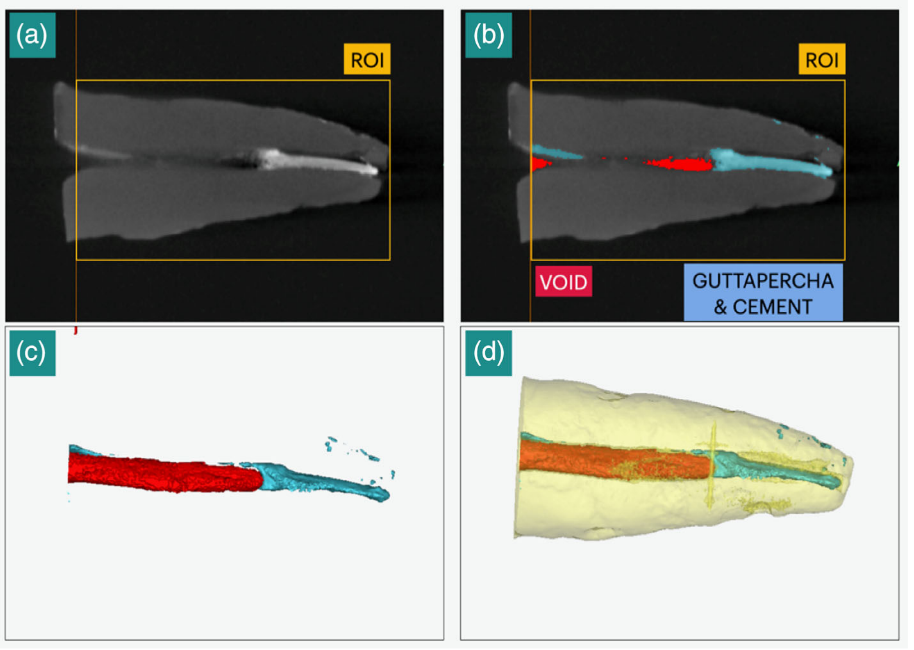

FIGURE 1 Representative images of the applied workflow from raw image to 3D parts using the Mimics 20.0 software. (a) Represents the selection of the region of interest (ROI) that was standardized for all samples to ensure consistency between measurements. (b) Shows segmentation of voids (red areas) and radiopaque parts (light-blue areas). (c) and (d) Show the 3D rendering of the selected parts alongside transparent dentin (yellow volume).

application, a detachment attempt was made, pulling the post slightly upwards using a dental pincette; if the attempt was unsuccessful, the process was repeated. The time was recorded during post removal attempt, from the first ultrasonic/laser application till the post was finally pulled out. The preparation of the specimens, post cementation, and removal procedures were conducted by a single experienced operator to reduce inevitable bias.

2.4 | Assessment of changes in dentin and cement volumes after post removal

After post removal, the specimens were scanned again with micro-CT following the same protocol mentioned above in order to ensure consistency between greyscale values. Forty scans were acquired in total for the two groups after post preparation and post removal. Constructed images were inputted into VivoQuant ver.4.0 (Invicro, Boston, MA) and Mimics 20.0 (Materialize, Ann Arbor, MI) software for analysis. A standardized region of interest (ROI) was used in all samples to ensure consistency in data analysis. The coronal limit of the ROI was set the coronal part of the sample, while the apical limit was set at the anatomical apex of the tooth itself. 3D manual segmentation was performed with the ROI limits, in order to separate radiopaque materials (gutta-percha and residual cement) and voids contained inside the root canal system, as done by previous studies (Comba et al., 2021). This procedure was possible thanks to the differences in terms of greyscale values between the analyzed parts. Boolean operations and region growing functions were also applied to improve the quality of the segmentation, while morphological procedures were unnecessary and therefore avoided in the present study protocol (Comba et al., 2021). An exemplificative summary of the procedure is reported in Figure 1, from raw images to 3D parts.

From the aforementioned process, dentin volume was calculated in mm^3 following the exact same steps in baseline and after-post removal samples. The so-obtained difference, representing the volume of dentin loss due to the post-removal procedure, was assessed for each sample and used for statistical analysis. Cement residues were also separately segmented, with the same protocol, to avoid biases in the calculation of both dentin volume loss and for separate analysis of the residuals after the procedure. After exporting the void volumes in high-quality .stl format, 3D rendering comparison with dedicated software (Geomagic Studio 12, 3D Systems) was used to check, through color map, the effects of the procedure on the original post-space anatomy. In order to do that, the best-fit algorithm was used, with the following parameters: baseline = reference volume, sample size = 1500, tolerance <0.1 mm, fine adjustments = on. Figure 2 represents an example of the obtained comparison with both linear and volumetric differences. Positive differences in the profile of the root canal system represented by the yellow-to-red color scale, mean that the volume of dentin has been reduced compared to baseline. On the other hand, negative differences represented by the green-to-blue scale color indicate that cement residuals are present in that area.

2.5 | Assessment of micro-crack formation after post removal

The assessment of fiber post removal methods in terms of microcrack formation was implemented following micro-CT analysis. A total of 300 longitudinal sections of post space preparation and 300 longitudinal sections of post space removal were studied using micro-CT scans of each sample. Microcracks in each section were first identified and then quantified. For the credible comparison of the number of

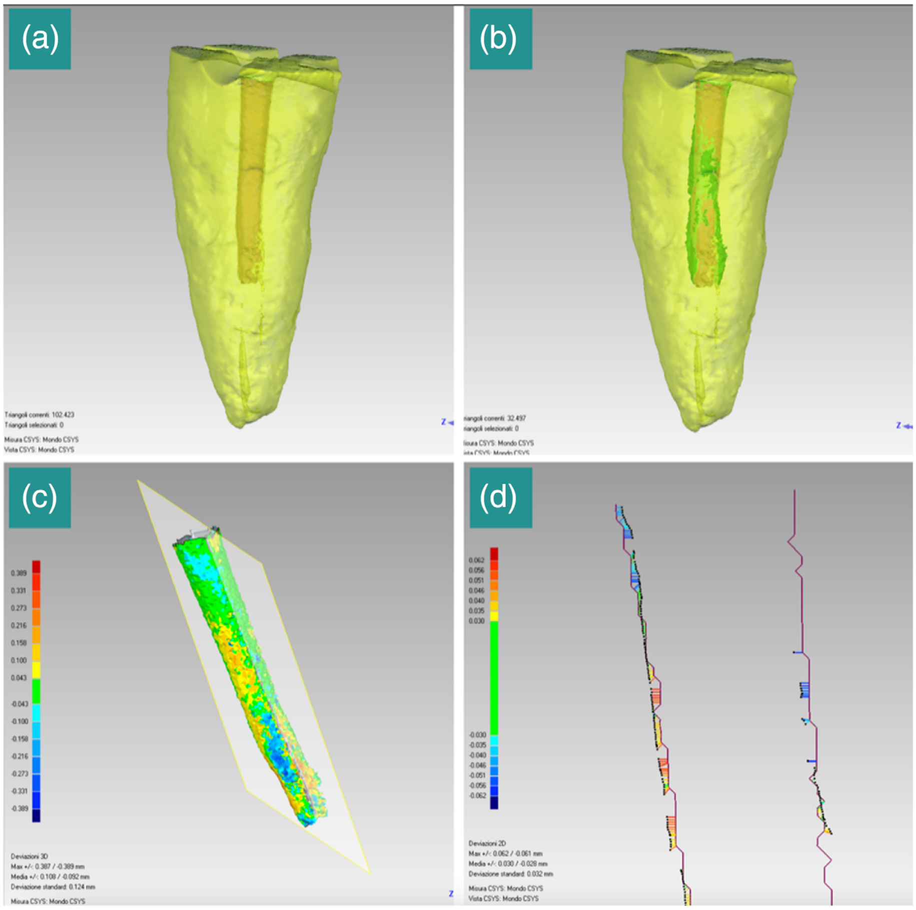

FIGURE 2 Representative images of data comparison: (a) shows the post-space volume (orange volume) inside the dentinal structure (yellow volume) at baseline, (b) shows the superimposition of the void volume after fiber post removal (green volume) on the same sample, (c) shows a color map generated through surface 3D comparison that highlight areas of dentin removal (yellow to red) and cement residuals (green to blue), and (d) shows the same comparison among a randomly selected slice visible in (c).

microcracks (preoperative and postoperative) co-registration (superimposition) of the Dicom image sets was conducted via the Re-orientation/Registration tool of Vivoquant software and more precisely by implementing the affine registration, which is a linear transformation. On these new datasets, with the aim of automatically detect micro-crack presence and progression, samples were initially checked with the aforementioned segmentation software (Mimics 20.0, Materialise, Ann Arbor, MI). For this purpose, a new ROI was created corresponding to void-filled total dentin volume. At this ROI, all voids were highlighted using morphology operations alongside a 3D-rendering preview of the result, as shown in Figure 3.

In case of crack detection at baseline, the same procedure was followed on the sample after the treatment, to ensure consistency of data and better visualization of gap progression. After crack detection, cross-section images were screened manually (total number of sections scanned, $n = 12{,}000$) by two pre-calibrated examiners. The number of cross-sections in which a dentinal micro-crack was found, was recorded after postoperative pictures were evaluated. Subsequently, the preoperative equivalent cross-sectional image was analyzed to confirm the defect's presence. Image analyses were conducted again to verify the results of the screening process after a period of 2 weeks and if there was any divergence, then the images were re-evaluated until the results were coincided.

The following definitions served as the basis for identifying a defect: (a) incomplete crack (crack line from the canal wall without reaching the external surface of the root), (b) complete crack (crack line extending from the root canal wall to the outer surface of the root), and (c) craze lines (crack lines observed in the root that do not reach any external surface of the root or lines extend from the outer surface of the root but do not reach the canal wall) (Landrigan et al., 2010).

Voxel size is considered the most important parameter during micro-CT scanning. In this study based on the voxel size of the micro-CT, fracture lines and major microcracks were detected as a preliminary examination of cracks, so no classification of dentinal defects was made. The percentages of sections with new microcracks were calculated in both groups. Representative images used for evaluating microcrack formation in longitudinal sections are presented in Figure 3.

2.6 | Statistical analysis

SPSS Statistics version 27.0 (IBM, Armonk, NY) was used for the statistical analysis. Power analysis was used for determining the appropriate number of teeth, and the statistically minimum number of teeth was calculated as 10 for each group ($n = 10$) after conducting a pilot study. Statistical analysis of the data was performed by using paired t-test, Wilcoxon-signed rank and Mann–Whitney U tests at a level of significance $\alpha = 0.05$. The normality and homogeneity of the data

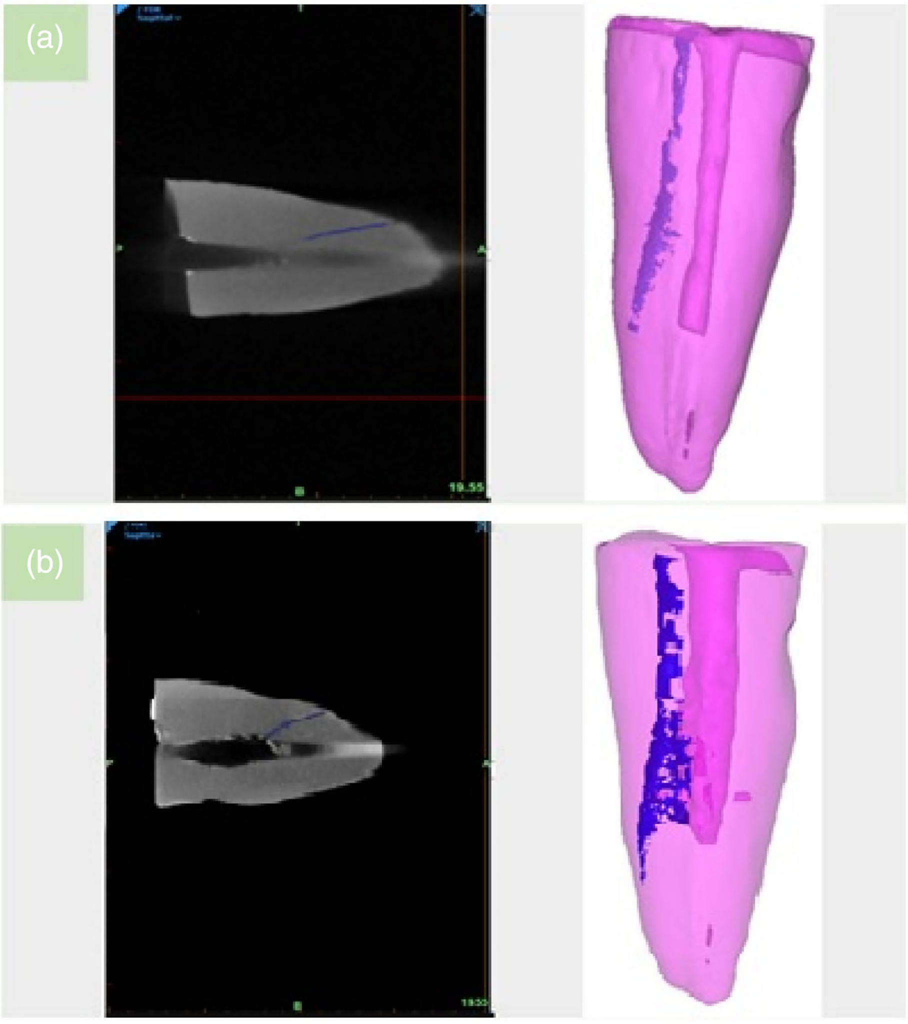

FIGURE 3 Representative images of a root specimen in longitudinal section before (a) and after (b) fiber post removal, for detecting microcrack formation using micro-CT. The direction and size of the formed microcracks are indicated with blue color.

TABLE 1 Means and standard deviations of dentin volume loss (mm^3), volume of cement and post residue in mm^3, number of sections with newly formed microcracks after post removal and removal time in min for both experimental groups ($n = 10$).

	n	Ultrasonic group	Laser group
Dentin volume loss (mm^3)	10	7.3 ± 2.1[a]	6.2 ± 2.2[a]
Volume of cement residue (mm^3)	10	0.18 ± 0.24[a]	0.17 ± 0.03[a]
Sections with newly formed microcracks	10	42 ± 27[a]	21 ± 16[b]
Removal time (min)	10	9.2 ± 1.0[a]	4.7 ± 1.1[b]

Note: Same lowercase superscripts in rows indicate no statistically significant difference between the groups ($p > .05$).

were predetermined using Shapiro–Wilk and Levene's tests, respectively.

3 | RESULTS

Both ultrasonic and laser treatments were efficient in removing fiber posts. The mean dentin volume decreased after removal in both groups ($p < .05$). Table 1 shows that there were no significant differences in the dentin volume loss and the amount of volume of post or resin cement residues between the experimental groups after post removal ($p > .05$). In both experimental groups, deviations from the initial root canal morphology occurred, but no perforations were observed. The number of microcracks was significantly lower in the laser group compared to ultrasonic group ($p < .05$). The mean

TABLE 2 Means and standard deviations of percentages (%) of the types of cracks after post removal for both experimental groups.

	Ultrasonic group	Laser group
Incomplete cracks	88.77 ± 24.51[a]	79.64 ± 35.29[a]
Complete cracks	4.84 ± 6.35[a]	18.73 ± 26.76[a]
Craze lines	5.39 ± 3.82[a]	1.46 ± 5.48[a]

Note: Same lowercase superscripts in rows indicate no statistically significant difference between the groups ($p > .05$).

percentages of the sections with newly formed microcracks for both groups are also presented in Table 1. Finally, the removal time was significantly shorter for the laser group compared to the ultrasonic group (p < .05), as it is revealed in Table 1.

The distribution of types of cracks formed after the post removal process according to the classification adopted in the present study is presented in Table 2.

4 | DISCUSSION

Based on the results of the present study, $H_0$1 was accepted. This is in agreement with Cho et al. (2022), who also reported no significant differences in dentin volume loss between Er,Cr:YSGG laser (6.499 mm^3) and ultrasonic (7.418 mm^3) post removal treatments. In the current study, the mean dentin volume loss of laser and ultrasonic groups was similar. This evidence implies that dentin loss during post removal is not crucially affected by the applied technique but it might be influenced by other factors such as the thickness of the resin cement around the apical part of the post and the diameter of the tool application tip, which is in contact with the dentinal walls of the root canal (Haupt et al., 2018; Purger et al., 2021). Although the differences in dentin volume loss between the two post removal techniques were not statistically significant, in both studies the Er,Cr:YSGG laser method presented slightly lower values. This may be due to the small spot size of the laser beam, which enables more accurate control of laser irradiation, in contrast to the ultrasonic treatment, which is more difficult to direct the active vibrating tip to the area of application (Cho et al., 2022). In the previous study (Cho et al., 2022), higher amount of dentin was removed in the coronal part of the root canal by the ultrasonics compared to laser. This is important for the fracture resistance of the root because cervical dentin is more valuable for the strength of the remaining tooth tissues, considering that coronal dentin is more prone to vertical root fracture (Sabeti et al., 2018; Silva et al., 2021).

Dentin volume loss during ultrasonic treatment can be attributed to micro-fractures of dentin, which are induced by the repeated stress application during the vibration of the ultrasonic tip (Arukaslan & Aydemir, 2019). Since it is difficult for the dental clinician to distinguish resin cement from dentin during fiber post removal procedure, it often leads to sacrificing dentin tissue, as well as increasing intracanal temperature (AlBalkhi et al., 2018; Deeb et al., 2019). This transfer of kinetic energy and simultaneously the induced heat in the area of tip application facilitates the degradation of the structure of dentin and as a consequence dentin volume loss.

On the other hand, dentin volume loss during Er,Cr:YSGG laser treatment may be explained by the fact that the thickness of the resin cement around the apical part of the post was less than the diameter of the tool application tip. Thus, doubtlessly some amount of laser energy is directed towards the dentinal walls. Although the laser tip was positioned at the post-dentin interface as perpendicular as possible, the active tip was in close contact with the root canal walls. Generally, the light energy produced by a laser beam can have four different interactions with dentin; reflection, transmission, scattering, and absorption. When laser energy is absorbed, it increases the temperature and produces photochemical effects depending on the water content of the tissue. When the temperature approaches 100°C, vaporization of water occurs, which results to creation of enormous subsurface pressure that can lead to the explosive removal of the surrounding mineral matrix; a process known as thermomechanical ablation (Apel et al., 2002). On the other hand, when temperature is below 100°C, but above approximately 60°C, denaturation of the proteins of dentin begins without vaporization of water. Moreover, at temperature above 200°C, the tissue is dehydrated and then burned, resulting in an undesirable effect called carbonization (Carroll & Humphreys, 2006; Sulieman, 2005). It has been demonstrated that the ablation threshold of dentin for Er,Cr:YSGG laser is 2.69–3.66 J/cm^2 (Lin et al., 2010). In the current study the fluence of laser pulse was 63.77 J/cm^2, which was much higher from the ablation threshold of dentin for Er,Cr:YSGG laser radiation intending to remove the resin cement.

The outcomes of the present investigation demanded accept of $H_0$2. In fact, no significant difference was observed in the amount of residual material (resin cement and post-residue) between the two experimental groups. The 3D manual segmentation described in the methodology was used to distinguish residual material inside the root canal in order not to be calculated as radiopacity (root dentin) and influence dentin volume loss measurements. Haupt et al. (2022) postulated that the volume of residual material is negatively correlated with the amount of removed dentin, regardless the post removal technique. This study found that ultrasonics removed higher dentin volume compared to the other methods tested may be due to the conical geometry of the tip which had coronal diameter of 1.5 mm. In the current research, the coronal diameter of the ultrasonic tip was approximately 1 mm, while the diameter of the laser tip was 0.5 mm. This difference in the diameter of the tips may partially justify the outcomes of the present investigation regarding the removal of similar dentin volume and residual material by both treatments.

It has been claimed that debonding occurs mainly inside the internal structure of the resin cement, leaving a large amount of residual resin cement attached either to the post or to the root canal walls (Rodrigues et al., 2017; Cho et al., 2022). In the current investigation, a small amount of residual material was observed inside the dentinal walls in all specimens of both treatments. As a result, fiber post removal with ultrasonic tips or Er,Cr:YSGG laser did not effectively clean the dentinal walls. The mechanism of action of Er,Cr:YSGG laser to remove cemented fiber posts involves decrease in the shear bond strength of the post to dentin, because it emits at 2780 nm that almost coincides with the maximum absorption peak for water, residual monomers (in resin cements), and hydrated tissues (Alikhasi et al., 2019). Consequently, the micro-explosions of water and monomers that carried out inside the structure of cement results in degradation and removal of the material.

As the statistical analysis revealed, $H_0$3 was rejected. More specifically, the number of sections that newly formed microcracks were observed in laser group was almost half of that of ultrasonic group.

This finding may be attributed to the nature of laser energy because there are no mechanical forces that may induce apically stress and strain concentrations, resulting in crack formation or propagation. The fact that Er,Cr:YSGG laser treatment creates much lower number of microcracks might be important in the long-term survival of the endodontically treated teeth (Altshul et al., 1997; Çapar et al., 2015; Yoldas et al., 2012).

Post removal treatments often raise concerns about the appearance of cracks or fracture lines that can propagate under repetitive occlusal forces (Arukaslan & Aydemir, 2019; Haupt et al., 2018). Regarding ultrasonic treatments, in the previous study no significant difference in microcrack formation was reported between a conventional ultrasonic treatment and a removal kit treatment (Arukaslan & Aydemir, 2019). Nevertheless, there are no data in literature concerning the formation of microcracks during Er,Cr:YSGG laser post removal treatments. Prevention of crack formation should be a critical parameter in selecting an appropriate method for removal of fiber posts, and as a consequence the outcomes of this study provide clinical significance.

To the author's knowledge in the current literature only three studies have evaluated the formation of microcracks during fiber post removal (Çapar et al., 2015; Arukaslan & Aydemir, 2019; Haupt et al., 2022). There are two distinct approaches for evaluating formation of microcracks. Firstly, destructive tests can be conducted by postoperatively cutting the samples in sections followed by stereoscopic analysis for microcrack identification (Arias et al., 2014; Liu et al., 2013; Stringheta et al., 2017). Nevertheless, the cross-sectioning analysis revealed that the destructive method itself may induce the dentinal defects (Stringheta et al., 2017). On the other hand, nondestructive micro-CT is an accurate tool with improved precision that provides hundred of sections per specimen and enables evaluation of pre- and postoperative scans, as well as co-registration of the sections. Additionally, the specimens act as their own controls.

Besides, microcrack formation can also occur due to dehydration of dentin and the lack of periodontal ligament in ex vivo conditions. Shemesh et al. (2018), who focused on the effects of environmental factors on dentinal tissue, demonstrated that the biomechanical response of root dentin was significantly influenced by the degree of its hydration. Loss of water produced stresses sufficient to cause spontaneous dentinal defects. This is consistent with the results of earlier research that reported controlled microstrain concentrations in hydrated roots and that dehydrated dentin presented reduced toughness and increased brittleness (Kahler et al., 2003; Kruzic et al., 2003). However, the detection of microcracks in moist conditions is more difficult due to the lower contrast in water (Rödig et al., 2018). The findings of a previous report indicated that up to 24 h of tooth dehydration no development of new dentinal defects was observed (Rödig et al., 2018). For this reason, in the present investigation, the specimens were dried at room temperature for 2 h before scanning.

In addition, the periodontal ligament, which deflects forces applied to tooth tissues and stops the propagation of microcracks following various endodontic operations are of great importance for the formation of new microcracks. An artificial periodontal ligament was developed in the current study to mimic these functions, although it is undoubtedly unable to replicate the original periodontal system. Earlier recent studies supported the use of an in situ fresh cadaver model, where the bone and periodontal ligament were preserved, simulating the in vivo conditions (Arias et al., 2014; De-Deus et al., 2017).

Obviously, dentin removal is not the only factor that may create microcracks and lead to fracture. Correlation analysis between dentin removal and formation of microcracks revealed no significant results (Haupt et al., 2022). In the present study, another factor that should be considered as cause for the decreased number of microcracks in the laser group is the time of application. In particular, the time needed to remove fiber posts with laser was the half compared to ultrasonics. The decreased duration of the energy application to dentin seemed to have an impact in microcrack formation as it was expected. Consequently, the effective time of application of a post removal technique may be crucial for the integrity of the remaining tooth tissues. Other factors that may influence microcrack formation in clinical conditions include patient age, type of restoration and parafunctional occlusal stress (Haupt et al., 2022; De-Deus et al., 2017).

The results obtained from this study indicated the rejection of $H_0$4. Glass fiber posts were removed in approximately 5 min using Er,Cr:YSGG laser, compared to almost 9 min using ultrasonic treatment. Similar results reported by Deeb et al. (2019), who compared an Er:YAG laser treatment with a conventional ultrasonic treatment. Different type of applied energy may interact differently with the resin cement in favor of laser light energy, which may degrade faster the structure of cement leading to acceleration of the removal of the posts (Aydemir et al., 2018; Arukaslan & Aydemir, 2019).

As it was mentioned before, Er,Cr:YSGG laser emits at 2780 nm and selectively targets the water and residual monomer molecules in the resin cement. This was the reason that in previous studies this laser wavelength was used for removing bonded restorations from natural teeth (Deeb et al., 2022; Giraldo-Cifuentes et al., 2020). It is important to note that dentin damage during post removal procedure can also be a result of temperature rise at the area of application. It has been found that the ultrasonic treatment induce higher amounts of heat during post removal procedure than laser treatments (higher temperatures ranged between 4°C and 13°C) (Deeb et al., 2019). This is due to heat production from the ultrasonic device through friction created between the post and the ultrasonic tip and kinetic energy absorption of ultrasound transmitted to the tooth (Bergeron et al., 2001). The increased temperature in case of the ultrasonic post removal treatments may also affect periodontal ligament and lead to root ankylosis, if the procedure lasts for a long time (Atrizadeh et al., 1971). Thus, it is crucial to achieve removal of the posts from roots as quickly as possible, so the use of Er,Cr:YSGG laser treatment may prevent further instrumental heating and heat transfer throughout the root due to its shorter clinical procedure.

Based on the limitations of the X-ray penetration depth (output of 50 kV) and the detector resolution of the micro-CT scanner used in the current study, it may be inferred that the results could indicate an underestimation of the problem. However, sequential analysis of the cross-section slices throughout the longitudinal axis of the root allowed the differentiation between genuine dentinal defects from artifact or noise (false-positive output) created in a single slice during image acquisition or reconstruction. Also, the use of software to co-register the image stacks allowed a precise analysis of the same image at the same point of the root before and after intracanal procedures.

5 | CONCLUSIONS

Within the limitation of this in vitro study it could be concluded that the tested Er,Cr:YSGG laser treatment was advantageous regarding microcracks formation and removal time compared to the ultrasonic treatment, indicating that the use of Er,Cr:YSGG laser could be an alternative fiber post removal technique. The loss of dentin during the fiber post removal procedure resulted in a significant reduction in volume in both groups. The above findings underline the importance of being minimally invasive in restoring the root canal system with a new core build-up and avoiding microcracks in the root dentinal walls. The results of the current investigation seem promising and could be important for long-term survival of structurally compromised teeth. However, clinical studies are necessary to confirm the effectiveness of the methods.

AUTHOR CONTRIBUTIONS

Ismini Papoulidou: Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Dimitrios Dionysopoulos**: Writing – original draft, Supervision, Project administration. **Petros Mourouzis**: Writing – review & editing, Visualization. **Olga Naka**: Writing – review & editing, Visualization, Methodology. **Kyriakos Sarris**: Writing – review & editing, Methodology. **Andrea Baldi**: Methodology, Investigation. **Nicola Scotti**: Methodolgy, Investigation. **Kosmas Tolidis**: Supervision, Conceptualization, Review & editing the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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