CLINICAL RESEARCH

Micro-computed Tomographic Analysis of the Efficacy of 3 Techniques for Removal of Calcium Hydroxide from the Mesial Canals of Curved Mandibular Molars

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ABSTRACT

Introduction: The purpose of this study was to evaluate the efficacy of **3** irrigation techniques: standard syringe irrigation (SI), ProUltra PiezoFlow (CUI)**,** and EdgeEndo Er,Cr:YSGG (LAI) laser in removing calcium hydroxide from the mesial canals of severely curved mandibular molars using micro-computed tomography (micro-CT) analysis. **Methods:** Mesial canals of 30 extracted human mandibular molar teeth were prepared to size 30/.04 taper or 35/.04 taper rotary instruments. Teeth were randomly assigned to the 3 experimental groups (n = 10) with evenly distributed degrees of curvature. Calcium hydroxide was placed into prepared canals and sealed for 14 days. A micro-CT scan was taken to determine calcium hydroxide paste volume in each tooth. Canals were irrigated utilizing the 3 techniques and re-scanned. Micro-CT volume and percent change of calcium hydroxide before and after irrigation were calculated and analyzed. **Results:** Calcium hydroxide paste remained in all groups after irrigation. The SI group removed −0.09% in the apical segment (0–3 mm) and 14% in the middle segment (3–6 mm). CUI removed 15% in the apical segment and 50% in the middle segment. LAI removed 49% in the apical segment and 72% in the middle segment. **Conclusions:** Irrigation with LAI removed significantly more calcium hydroxide in the middle and apical segments when compared to CUI and SI. *(J Endod 2025;51:1053–1060.)*

KEY WORDS

Calcium hydroxide; calcium hydroxide removal; syringe irrigation; continuous ultrasound irrigation; laser irrigation; micro-CT

SIGNIFICANCE

The study addressed removal of calcium hydroxide from the mesial roots of mandibular molars. LAI removed significantly more calcium hydroxide in the middle and apical segments when compared to CUI and SI. However, complete removal was not achieved.

Calcium hydroxide as an intracanal medicament has been shown to reduce bacterial load associated with pulpal necrosis[1]. It has also been proposed as an adjunct to ultrasonic irrigation to improve the reduction of bacteria within the canal system[2]. While it provides this benefit as an intracanal medicament[3], it is not easily removed from the anatomically complex root canal system[4] and it is clinically impossible to determine complete removal from an irregular canal wall[5,6]. Complete removal of calcium hydroxide from the root canal is important for the success of root canal treatment. Residual calcium hydroxide has been reported to have unwanted effects such as causing increased apical leakage[7], preventing sealer from penetrating the dentin tubules[8], and reducing dentin bond strength with sealers[9]. Thus, it is important for the endodontist to have a strategy to completely remove this medicament from the canal system.

Studies have compared the efficacy of calcium hydroxide removal using the following irrigation techniques: mechanical removal with files, syringe irrigation, sonic irrigation, passive ultrasonic irrigation, continuous ultrasonic irrigation, and laser activated irrigation[10–14]. Most studies comparing irrigation techniques have been performed using straight canals[4,11–13,15–17] without complete removal of calcium hydroxide[15–17]. When looking at curved canals, no irrigation techniques have shown complete success in the removal of the dressing[18–20]. Recent review articles have not directly compared EdgeEndo

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Er,Cr:YSGG (LAI) and continuous ultrasonic irrigation, but report that both methods are superior to syringe irrigation at removing calcium hydroxide, removing microorganisms, removing dentin debris and removing the smear layer[21–23].

Micro-computed tomography (micro-CT) allows for a three-dimensional imaging with a very high resolution, with a voxel range of 5–50 microns, which is nearly 1 million times smaller in volume than standard CT voxels[24]. It allows for volumetric analysis without the need for sample preparation or slicing, unlike analysis with scanning electron microscopy[25]. This allows for the examination of the internal adaptation of materials without destroying them[24]. Compared to cone-beam computed tomography, micro-CT has smaller voxel sizes and a longer exposure time. This allows for the detection of more subtle and smaller changes[26], which is particularly relevant for endodontic studies.

Therefore, the purpose of this study was to evaluate the efficacy of three techniques: standard syringe irrigation (27-gauge side-vented needle); continuous ultrasonic irrigation (ProUltra PiezoFlow); and laser activated irrigation (EdgePro), in removing calcium hydroxide from the mesial canals of curved mandibular molars using micro-CT analysis.

MATERIALS AND METHODS

Tooth Selection

Thirty extracted, human first and second mandibular molars were selected for this study from a collection over 100 mandibular molars (without knowledge of patient demographics) using the following inclusion criteria - intact mesial roots with closed apices, patent canals (as determined with a #10 K file after access opening), mesial root curvature considered severe (greater than 25°) as calculated from sagittal digital radiographs as described by Schneider[27], no signs of resorption or root fractures as evaluated under 4× magnification using a surgical microscope (Zeiss, Oberkochen, Germany), ability to remove distal root without damaging the mesial root. Exclusion criteria included presence of full coverage coronal restorations or coronal restorations comprising more than 50% of the coronal tooth structure, c-shaped roots/canal systems, immature roots, single-canal containing roots (Weine Type 1), roots with cracks.

Standard access preparation was accomplished, and the mesial canals were located. Patency and the working length of each canal was determined by placing a #10 K-file (Dentsply Maillefer, Ballaignes, Switzerland) into each canal until it was visualized at the apex with the surgical microscope under 4× magnification, and then the file was retracted 1 mm which was the determined working length. The distal root of each tooth was sectioned to the level of the furcation and the orifice was cleaned with rotary files (ProFile Vortex; Dentsply Sirona, York, PA). The external and internal distal root surface was acid etched and sealed with a resin composite (Herculite XRV Unidose, A3, Kerr, Brea, CA) and light cured.

Root Canal Preparation and Placement of Calcium Hydroxide

Initial glide path was prepared using a #15 K-file. Orifice shapers #25/0.12 and #40.0 (ProFile Vortex; Dentsply Sirona, York, PA) were utilized to achieve straight line access into the canals. Ethylenediaminetetraacetic acid (EDTA) gel (Glyde, Dentsply Maillefer, Ballaignes, Switzerland) was placed on each rotary file before use. Canals were shaped with nickel-titanium rotary instruments (Vortex Blue, Dentsply Tulsa Dental Specialties, Tulsa, OK) to a minimum size/taper of #30.04 and maximum of #35.04. Any root canals in which a 35.04 file reached the WL without cutting apical dentin were eliminated. Each canal was irrigated with 2 mL of 5.25% NaOCl delivered with a 27-gauge side vented needle (Henry Schein, Melville, NY) placed passively into each canal after every two instruments used. Patency was maintained between each rotary instrument with a #10 K-file.

After canal preparation, the canals were dried with paper points and calcium hydroxide paste containing barium sulfate for increased opacity (DiaPaste, DiaDent, Safeco Dental Supply, Buffalo Grove, IL), was placed into the mesial canals using the manufacturer's recommended tip until paste was visible at the root apex, as visualized with the surgical microscope under 4x magnification. The pulp chamber was cleaned of excess paste with a damp cotton pellet. A radiograph was taken from the sagittal view to confirm the presence of calcium hydroxide in the canals to the apex. The access opening was temporarily sealed with a cotton pellet and 3 mm depth of temporary restoration (DuoTemp, Coltene USA, Cuyahoga Falls, OH). The root apices were then sealed with lab putty (Sil-Tech, Ivoclar Vivadent, Amherst, NY). A micro-CT image (μCT 50, cabinet cone-beam microCT, Scanco Medical, Switzerland) was captured to measure the volume of calcium hydroxide present in each experimental group. The teeth were stored in 100% humidity for 14 days.

Calcium Hydroxide Removal

All sample teeth were ranked from smallest to largest angle of curvature. The teeth were then divided into ten groups of 3 (example group 1: 1, 2, 3; group 2: 4, 5, 6, etc). Within the group of 3 teeth, random numbers were assigned, utilizing Microsoft Excel (Microsoft Excel, Microsoft Corporation, Redman, WA), to each tooth in each experimental group a, b or c (example group 1: 1c, 2b, 3a; group 2: 4b, 5a, 6c, etc.). Randomization was used to distribute angles of curvature evenly among the three experimental groups rather than ranking and assigning a,b,c, b,c,a, etc. so that group a didn't end up having all smaller angles and group c having all larger angles. Each irrigation group had a range of curvature of 31.7–45.8 for SI, 25.7–60.1 for LAI, and 27.9–50.4 for CUI. The average degree of root curvature for the 3 irrigation groups ranged from 38.4° to 39.3°. There was no significant difference in the distribution of mesial root curvature among the 3 groups.

All teeth were mounted in a Protrain endodontic simulator (Protrain, Simit Dental, Mantova, Italy) with apices sealed with lab putty as previously described. The temporary restorations and cotton pellet were removed, and the calcium hydroxide was removed by group following the experimental protocol described below. A final micro-CT scan was acquired to evaluate the amount of calcium hydroxide remaining in the canals.

GROUP 1 STANDARD NEEDLE IRRIGATION (SI)

The removal of calcium hydroxide was performed with standard needle irrigation with a 10 mL syringe (Henry Schein, Melville, NY) and 27-gauge side-vented needle (Henry Schein, Melville, NY) using 5.25% NaOCl. A bend was placed in the needle at 1 mm less than the established working length and an endodontic rubber stopper was placed on the needle. Two 10 mL syringes were utilized for irrigating each canal. The first was filled with 10 mL of NaOCl and the second was filled with 5 mL of NaOCl. The needle was inserted passively into each canal until it met resistance and then retracted 2 mm. In 3 teeth, the needle never met resistance and went to the apex. Therefore, irrigating to the apex would pose a safety issue clinically and predispose these teeth to a possible cleaner apical area. These 3 teeth were deleted from the analysis in this group. NaOCl was delivered to each canal with an up and down motion utilizing a surgical suction. When the first syringe was empty, the same 27-gauge needle was removed from the first syringe and Luer-locked on the second to deliver the remaining 5 mL of NaOCl, for a total of 15 mL per canal. Any remaining irrigant was suctioned from the chamber and a dry cotton pellet was placed into the chamber.

GROUP 2 CONTINUOUS ULTRASONIC IRRIGATION (PROULTRA PIEZOFLOW) (CUI)

The removal of calcium hydroxide was performed with continuous ultrasonic irrigation using the ProUltra PiezoFlow 25-gauge ultrasonic needle (Dentsply Sirona, York, PA). The needle was used in conjunction with an Acteon ultrasonic module (Acteon group, Lyon, France) incorporated into an ASI cart (Advanced Endodontic Systems Englewood, CO) to provide energy for tip oscillation at a power setting of 10. Irrigant (5.25% NaOCl) was delivered at a continuous rate of 15 mL/min in conjunction with the ASI cart pump. The inactive PiezoFlow needle was inserted passively into each canal until it met resistance and then retracted 2 mm. Irrigant flow began, and the needle was passively moved in an up-and-down motion for 1 minute per canal as per manufacturer recommendation. Any remaining irrigant was suctioned from the chamber and a dry cotton pellet was placed into the chamber.

GROUP 3 LASER ACTIVATED IRRIGATION (EDGEPRO MICROFLUIDIC IRRIGATION) (LAI)

The removal of calcium hydroxide was performed with laser activated irrigation using the EdgePRO Microfluidic Irrigation Er,Cr:YSGG laser (EdgeEndo, Albuquerque, NM). The water and NaOCl modes (water mode specifications - 25 mJ, 1.25 W, 50 Hz with 20% air and 20% distilled water, NaOCl mode specifications - 25 mJ, 1.25 W, 50 Hz with 0% air and water) were utilized for each canal. A size 1 tip (200 μm fiber core diameter) was placed into the canal to 1–2 mm from WL and water mode was activated. The tip was removed from the canal at a rate of 1–2 mm per second while firing the laser and this action was repeated three times per canal, as per manufacturer instructions. The chamber was then flooded with 5.25% NaOCl and the laser tip was placed halfway down the canal and solutions mode was activated. The tip was again removed at a rate of 1–2 mm per second while firing the laser and this was conducted three times per canal, as per manufacturer instructions. Any remaining irrigant was suctioned from the chamber and a dry cotton pellet was placed into the chamber.

MICRO-COMPUTED TOMOGRAPHY IMAGING AND EVALUATION

A total of 60 micro-CT scans were performed for the study. Each tooth was imaged 2 times: after $Ca(OH)_2$ paste placement, and after $Ca(OH)_2$ removal. For the scan after $Ca(OH)_2$ paste placement and after $Ca(OH)_2$ paste removal, teeth remained mounted in lab putty as previously described. Three teeth at a time were placed vertically into a 19 mm diameter cylinder (U50824, Scanco Medical, Switzerland) with foam to act as a spacer between samples and sealed with the lid (U50894, Scanco Medical, Switzerland). A thin strip of ParaFilm M (Amcor, Zurich, Switzerland) was placed on the external surface of the tube to seal between the cylinder and lid. All scans were completed with $10 \times 10 \times 10\ \mu m^3$ voxels, imaged at 70 kVp, 76 μA with a 0.5 mm Al filter, and integration time of 900 ms.

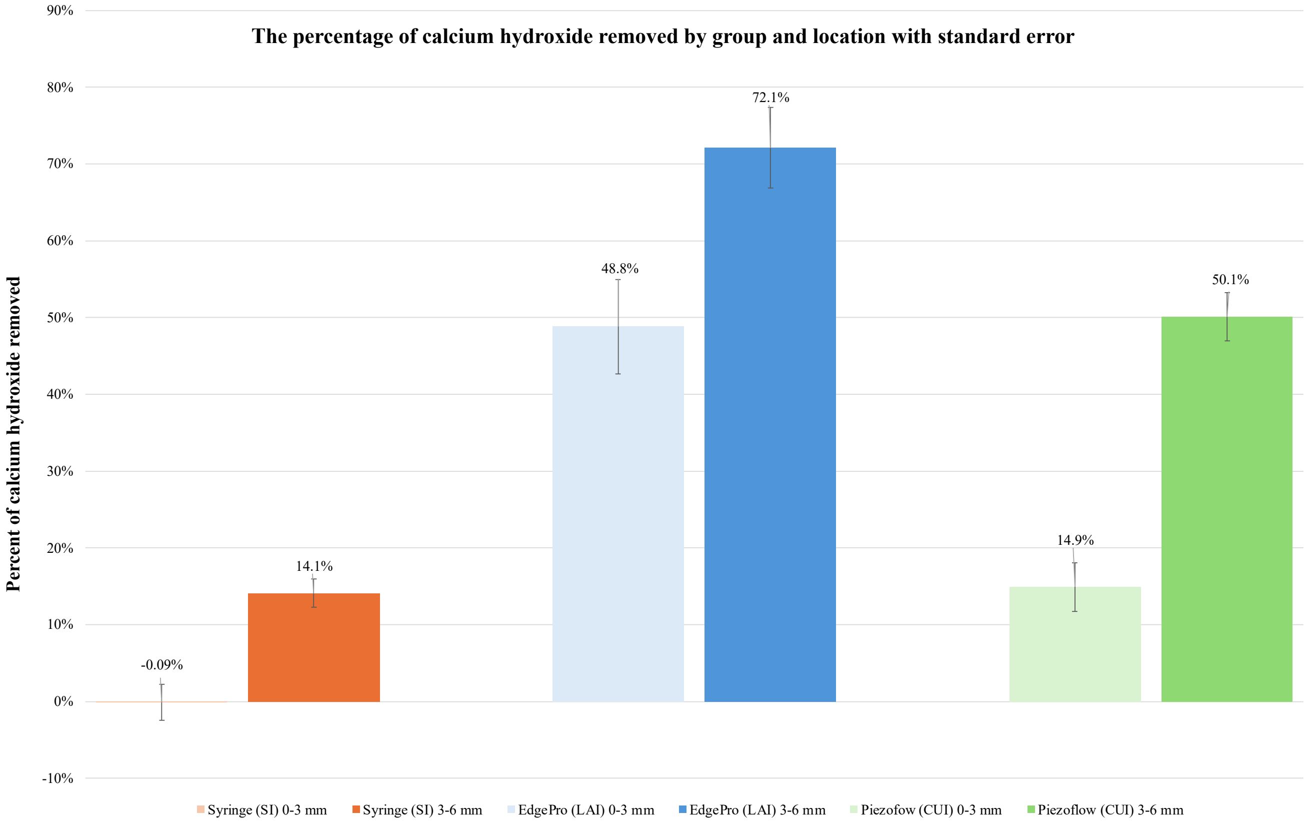

FIGURE 1 – Percentage of calcium hydroxide removed by group and segment with standard error. SI, Syringe; LAI, EdgePro; CUI, PiezoFlow.

TABLE 1 - Anova Main Effect Summary

Effect	Estimate	Se	F-Stat	df	*P* value
Intercept	0.06	0.07	0.75	27.9	.454
Effect of LAI vs SI	−0.53	0.09	−5.71	24.0	<.000
Effect of CUI vs SI	−0.25	0.09	−2.72	24.0	.012

SI, Syringe; LAI, EdgePro; CUI, PiezoFlow.
Intercept = effect of SI in 0–3 mm area, all effects are compared to intercept.
The effect of LAI and CUI were statistically significant when compared to SI.

Each raw scan image set consisted of greater than 600 slices in the Z plane. Scans were cropped to the size of the tooth in the X and Y planes and 1–300 slices (0–3 mm) in the Z plane where slice 1 corresponded to the apex of the tooth, and 300–600 slices (3–6 mm) in the Z plane corresponded to the 3–6 mm root level. The images were converted to DICOM files. All cropping and file conversion were completed by the senior author (JGE). DICOM files were imported into Analyze 14.0 software (AnalyzeDirect 14.0, Inc., Overland Park, KS), processed using signed 16 bit to convert the image into binary digits based on shades of gray. Once imported, the file was opened with the Transform tool and calibrated using the Image Algebra tab. Periodic quality control scans were run on the micro-CT unit to calibrate densities from the scans of the machine to the values recognized by Analyze 14.0 software (AnalyzeDirect 14.0, Inc., Overland Park, KS). The slope and intercept from quality control scan from the closest date to the sample scan were utilized to calibrate each scan.

Once scans were calibrated, each scan file was opened under the Segment tool. Under the Semi-Automatic tab, Threshold Volume was utilized to define the calcium hydroxide paste within the canal from the rest of the tooth. The Manual tab was then utilized to remove any errant areas from being included with the volume of calcium hydroxide (any areas outside of the canal with the same density as calcium hydroxide). This step was completed using a 3D rendering to remove the bulk of any artifacts in space, and then repeated along blocks of 10 coronal slices (300 slices total) to confirm only areas within the canal space were included as the volume of calcium hydroxide.

The Object Map, consisting of the volume of calcium hydroxide, was saved and then opened within the Measure tool. The Object Map was enabled to allow for the 3-D volume to be calculated and reported in mm^3. These values were recorded, and the percentage of calcium hydroxide was calculated. A negative value in the percent change indicated a decrease in the volume of calcium hydroxide.

With a two-sided alpha risk of .05 and assuming a calcium hydroxide removal rate of 50%, a sample size of 10 specimens per group was required to detect a difference of ± 30 percentage points in the calcium hydroxide removal with a power of > .88.

STATISTICAL ANALYSIS

All calculated volumes as well as percent change for each scan were statistically analyzed by a PhD statistician. An ANOVA was performed on the model to determine effect significance. Confidence intervals for the effect difference between each pair of methods were constructed using Tukey Honest Significant Difference Pairwise comparisons. Root curvature severity was statistically compared among the groups using ANOVA.

RESULTS

LAI was preferable to both SI and CUI methods in the middle and apical areas of the tooth (Fig. 1). Additionally, CUI was preferable to SI in the middle and apical areas of the tooth (Fig. 1). The ANOVA main effect summary is presented in Table 1. Confidence intervals are reported in Table 2.

The average percent removal of calcium hydroxide in the apical (0–3 mm) and middle (3–6 mm) segments of the mesial root canals in the syringe irrigation (SI), PiezoFlow (CUI) and EdgePro (LAI) groups are presented in Table 3 and Figure 1. Complete removal of calcium hydroxide was not achieved in any of the sample teeth. In the apical segment (0–3 mm) of the SI group, the average percent decrease of calcium hydroxide was negative, indicating that more calcium hydroxide was observed in the apical segment due to the SI method pushing calcium hydroxide apically.

Each irrigation group had a range of curvature of 31.7–45.8 for SI, 25.7–60.1 for LAI, and 27.9–50.4 for CUI. The average degree of root curvature for the three irrigation groups ranged from 38.4° to 39.3°. There was no significant difference in the distribution of mesial root curvature among the three groups as analyzed by ANOVA (*P*-value = .974).

Sample figures for before and after irrigation are presented for SI (Fig. 2), LAI (Fig. 3), and CUI (Fig. 4).

TABLE 2 - Confidence Intervals for the Difference in Average Percent Decrease of Calcium Hydroxide

Comparison	Estimate	95% CI lower	95% CI upper
LAI vs SI	−0.535	−0.754	−0.315
CUI vs SI	−0.255	−0.474	−0.036

SI, Syringe; LAI, EdgePro; CUI, PiezoFlow.
The estimate indicates the magnitude of the effect, with a negative number indicating the first method in the comparison is more favorable for calcium hydroxide removal.
Both LAI and CUI methods were better at calcium hydroxide removal than SI.

DISCUSSION OF RESULTS

In previous work, SI with a 27-gauge needle in combination with mechanical removal with a #25 hand file left 25–45% (55–75% removal) of calcium hydroxide paste on the walls of straight, single rooted extracted teeth regardless of the irrigation solution used[4]. In a more recent study, SI left up to 72% (28% removal) of calcium hydroxide dressing in the apical third and left up to 4.5% (95.5% removal) of calcium hydroxide dressing in the middle third of the mesial canals of mandibular molars[14]. In our study, SI removed an average of 0.09% in the apical segment (0–3 mm) and removed an average of 14% in the middle segment (3–6 mm) (Fig. 1). Not reporting on canal curvature by Lloyd et al[14] may be the reason for the discrepancy in findings between studies. The efficacy of calcium hydroxide removal by SI is highly variable and other studies have used different volumes and irrigating solutions that make it difficult for comparison[4,12-14,28]. Regarding the apical displacement of calcium hydroxide, the potential mechanism would be that it has been established that the effects of SI cannot extend more than 2 mm beyond the needle tip[9,10]; therefore, the repeated motion and large irrigant volume displaced calcium hydroxide from the middle segment (3–6 mm) to the apical segment (0–3 mm). The clinical implications would include more calcium

TABLE 3 - Average Volume and Percent Decrease of Calcium Hydroxide (CH) by Method

	Syringe (SI)	EdgePro (LAI)	PiezoFlow (CUI)
Apical 0–3 mm			
CH Fill (mm^3)	0.97 ± 0.25	0.90 ± 0.41	1.07 ± 0.89
CH Final (mm^3)	0.97 ± 0.28	0.44 ± 0.32	0.90 ± 0.78
Percent Decrease	−0.09% ± 12%	49% ± 32%	15% ± 17%
Middle 3–6 mm			
CH Fill (mm^3)	2.50 ± 0.82	2.28 ± 1.14	2.54 ± 1.66
CH Final (mm^3)	2.14 ± 0.70	0.74 ± 0.77	1.12 ± 0.50
Percent Decrease	14% ± 9%	72% ± 27%	50% ± 16%

CH Fill, the mean volume (mm^3) of placed calcium hydroxide; CH final, mean volume (mm^3) of residual calcium hydroxide after removal by method. Percent decrease, percent decrease in calcium hydroxide volume from fill volume to final volume. LAI had the best decrease in percentage of calcium hydroxide removal in the apical and middle segments, followed by CUI, and finally SI.

hydroxide in the apical segment which may lead to increased apical leakage[7], preventing sealer from penetrating the dentin tubules[8], and reducing dentin bond strength with sealers[9].

In our study, CUI removed an average of 15% of calcium hydroxide from the apical segment and an average removal of 50% from the middle segment (Fig. 1). This was significantly more removal than with the SI method (Table 3). A study by Yucel et al[28] evaluated removal of calcium hydroxide from straight canals using continuous ultrasonic activation (CUI), specifically the ProUltra PiezoFlow device. It is important to note that the flushing effect of the irrigant with this ultrasonic system is enhanced with a constant flow of irrigant into the canal system. Yucel et al[28] reported CUI had an average cleanliness score which was significantly higher than irrigation with an endodontic needle. The study also reported that the most of the remaining paste were found in the apical third of the canals, with lower scores in the middle third. Regardless of technique used, the differences between the apical and middle thirds were all significantly different[28]. While Yucel et al[28] reported a higher level of cleanliness in the CUI group than we found in the apical (15% removal) and middle (50% removal) segments (Fig. 1), it is important to note they utilized straight canals, where our study utilized canals with severe curvature. No studies evaluating the removal of calcium hydroxide from curved canals with CUI were found in the literature.

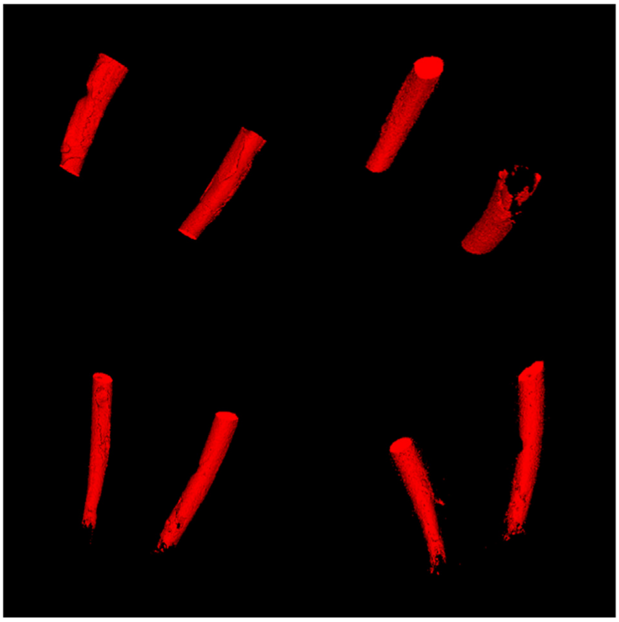

FIGURE 2 – Standard syringe irrigation (SI). Volume rendering before irrigation (*left*) and after irrigation (*right*).

In our study, LAI removed an average of 49% of calcium hydroxide in the apical segment and 72% of calcium hydroxide in the middle segment (Fig. 1). The settings (listed in the Methods section) were used with a 200 μm radial tip placed to the mid root of the canal. The adjustable settings of lasers make comparisons to other studies difficult. Increased pulse energy (measured in mJ), increased tip diameter, increased depth of penetration[29] and shorter pulse duration all can lead to increased cavitation of the irrigating solutions[30]. A higher input of laser energy results in greater cavitation bubbles[31]. Even though 2 lasers can utilize the same wavelength and pulse energy, they can have different effects based on the other parameters.

When laser energy is absorbed by water, a primary vapor bubble forms and then quickly and forcefully implodes[32,33]. Within the root canal system the implosion of the primary bubble leads to cavitation from the formation of new, smaller, intracanal bubbles throughout the canal[34]. As a result, contents of the root canal system are displaced coronally[30]. The secondary intracanal bubbles implode as well, which results in a very fast up and down movement of canal contents due to fluid velocities that are 10 times higher than those achieved with an ultrasonically oscillating file. EdgePro, the manufacturer of Er,Cr:YSGG lasers in conjunction with Biolase, recommends placement of the fiber tip into the canal while pulses are delivered on the withdrawal motion from the canal[30]. The vertical movement of the fiber tip produces the same cavitation effects throughout the entire root canal system. Currently, there are no guidelines, evidence, or consensus regarding the optimal LAI parameters for endodontic irrigation[30].

In a 2016 study comparing calcium hydroxide removal in artificial grooves in mandibular premolars with straight canals, Kustarci et al[35] found that LAI with Er,Cr:YSGG utilizing NaOCl resulted in an average of 20% residual calcium hydroxide (80% removal). The calcium hydroxide removal from the artificial groove was like the calcium hydroxide removal in the middle segment in our study.

The 10 samples per group was based on previous studies[17–19] comparing irrigation methods in extracted teeth, this number was considered the norm and provided enough power to establish significance[17–19].

It should be noted that publications evaluating removal of calcium hydroxide with ProUltra PiezoFlow are limited and no publications could be found regarding the

FIGURE 3 – EdgeEndo Er,Cr:YSGG (LAI) laser. Volume rendering before irrigation (*left*) and after irrigation (*right*).

removal of calcium hydroxide with the EdgePro laser.

This is the first study to evaluate the removal of calcium hydroxide from the root canal system using the EdgePro laser. Without published guidelines[30], the manufacturer's recommended settings were used and LAI with the EdgePro laser performed significantly better than CUI and SI at removing calcium hydroxide from canals with severe curvature. The Water step was initially added to the protocol to equalize the volume of irrigant used. Because the fiber tip diameter (0.2 mm) was smaller than both the 27-gauge needle (0.4 mm) used in SI and 25-gauge needle (0.5 mm) in CUI, it was able to advance to within 1–2 mm of the working length. Because the Water step does not utilize NaOCl, advancement to this depth of the canal was not as much of a clinical concern. In addition, the fiber tip was more flexible and freely advanced to this depth in all study teeth. This step may have created a loosening effect of the calcium hydroxide that did not occur in the SI or CUI groups. While the laser results were significantly better, complete removal of the calcium hydroxide from the canal system was not achieved. Further studies are indicated to increase removal of calcium hydroxide with the Edge Pro.

FIGURE 4 – ProUltra PiezoFlow (CUI). Volume rendering before irrigation (*left*) and after irrigation (*right*).

While the complete removal was not achieved by any method, the clinical implications would be increased apical leakage[7], preventing sealer from penetrating the dentin tubules[8], and reducing dentin bond strength with sealers[9]. Potential strategies to overcome the limitation of complete removal would be future studies exploring the technologies of Edge Pro by using more efficient settings and/or increased time of application which may result in the removal of more calcium hydroxide.

The exact clinical significance of the volume or percentage of residual calcium hydroxide paste remaining that might compromise treatment outcomes is not known. However, we can state that complete removal of calcium hydroxide would be the best outcome clinically.

Regarding choice of the irrigation needle size for the SI group, an apical size of 0.3 mm is needed for a 27-gauge irrigation needle to advance to within 1–2 mm of the apex[36,37]. All teeth in the study were prepared to a final apical size of 30/.04 taper or 35/.04 taper. Any teeth with canals larger than a 35/.04 taper were excluded from the study. For the CUI and LAI, the irrigation needle type and diameter were predetermined by the manufacturer so there was no choice of needle size.

In conclusion, the EdgePro Er,Cr:YSGG laser, using a protocol Water mode and NaOCl mode, removed significantly more calcium hydroxide from the mesial roots of mandibular molars with severe curvature than the ProUltra PiezoFlow irrigating needle or irrigation with a 27-gauge side vented needle. The ProUltra PiezoFlow irrigating needle removed significantly more calcium hydroxide than irrigation with a 27-gauge side vented needle under the same study conditions. All methods removed significantly more calcium hydroxide in the middle segment than the apical segment.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Jenna Gaudio Edwards: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **John Nusstein:**

Conceptualization, Methodology, Formal analysis, Investigation, Supervision, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Melissa Drum:** Conceptualization, Methodology, Formal analysis, Investigation, Supervision, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Sara Fowler:** Conceptualization, Methodology, Formal analysis, Investigation, Supervision, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Al Reader:** Methodology, Formal analysis, Investigation, Writing – review & editing, Visualization.

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The authors deny any conflicts of interest related to this study.

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