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Original Article

Effect of tip insertion depth and irradiation parameters on the efficacy of cleaning calcium hydroxide from simulated lateral canals using Er:YAG laser- or ultrasonic-activated irrigation

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Abstract *Background/purpose:* Laser-activated root canal irrigation (LAI) with an Er:YAG laser is considered more effective than other irrigation methods, whereas the effectiveness of LAI in cleaning lateral canals far from the laser tip remains unclear. This study aimed to compare the efficacy of removing calcium hydroxide [$Ca(OH)_2$] paste from lateral canals using LAI or ultrasonic-activated irrigation (UAI), and to examine the effect of tip insertion depth and laser irradiation parameters on cleaning efficacy.
Materials and methods: Radiopaque $Ca(OH)_2$ paste (Calcipex II) was injected into lateral canals 6 mm from the root apex in 192 J-shaped simulated root canal models. LAI (Erwin AdvErl; 30 or 70 mJ; 10 or 20 pulses per second; laser tip R200T or R600T) and UAI (ENAC SE10; output setting: 3) were performed 3 times for 20 s. The laser tip was placed at 8–0 mm coronal to the lateral canal location. The volume of $Ca(OH)_2$ paste before and after the experiment was measured using micro-CT (SMX-100CT).
Results: The $Ca(OH)_2$ removal rate by LAI was significantly higher than UAI at all tip insertion depths. $Ca(OH)_2$ removal rate in LAI was significantly lower at the 8 mm position compared with other positions ($P < 0.05$). When the tip insertion depth was fixed at this position, $Ca(OH)_2$ removal rate increased significantly when pulse energy and tip diameter were increased ($P < 0.05$).
Conclusion: LAI removed $Ca(OH)_2$ paste from lateral canals away from the tip more effectively than UAI. Increasing the pulse energy and tip diameter improved the removal efficiency.

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Introduction

Apical periodontitis is a bacterial inflammatory disease caused primarily by infection of the pulp tissue.[1] The main objective of endodontic treatment is to prevent or treat apical periodontitis by eradicating intracanal pathogens.[2] Root canals are usually cleaned mechanically, but the removal of pathogens from complex areas, such as lateral canals, fins, isthmuses, and oval canals, is limited.[3] Therefore, chemical disinfection methods such as root canal irrigation and intracanal medication must be used in the areas mechanical cleaning cannot reach.

Root canal irrigation is usually performed using a syringe and irrigation needle. However, this method is often insufficient, especially when the infection source is located inside a lateral canal.[4,5] Therefore, in recent years methods that involve agitating an irrigant have been developed to improve the cleaning effect in complex root canal areas. These include ultrasonic-activated irrigation (UAI)[6,7] and laser-activated irrigation (LAI).[8–10]

UAI uses a file that vibrates ultrasonically at 25–30 kHz to agitate the irrigant, which enhances the cleaning of root canals by generating cavitation and acoustic streaming.[6] Previous reports that examined the efficacy of cleaning complex root canal morphologies, such as artificial grooves, isthmuses, and lateral canals in extracted teeth or simulated models, found that UAI was more effective than syringe irrigation.[7,11–13]

LAI with an erbium, chromium: yttrium-scandium-gallium-garnet laser (Er,Cr:YSGG) or erbium: yttrium aluminum-garnet (Er:YAG) laser generates shock waves accompanied by the rapid generation and collapse of vapor bubbles from cavitation, which creates a fast flow of fluid and agitates the root canal irrigant to exert the cleaning effect.[8,10,14] Compared to UAI, LAI has been reported to have either similar[15–18] or significantly better[9,19,20] cleaning efficacy in root canal and apical areas with complex morphologies.

However, for root canal irrigation to be performed effectively while avoiding irrigant extrusion outside the apical foramen, it is preferable if the effects of irrigation can be obtained with the tip located away from the root apex. With LAI, the amounts of pressure outside the apical foramen and of the extruded irrigant increase depending on the tip insertion depth and output energy,[21–26] and the cleaning efficacy decreases as the distance from the tip increases.[27] However, opinions remain divided on the capacity of LAI to clean areas away from the tip, with some studies finding greater efficacy than UAI[15] and others reporting similar efficacy to syringe irrigation.[28]

Calcium hydroxide paste [$Ca(OH)_2$] is widely used as an intracanal medication, and has been suggested to have a disinfection effect on lateral canals.[5] However, another study has found that the disinfection effect of $Ca(OH)_2$ on lateral canals is insufficient.[29] Further, remnants of $Ca(OH)_2$ in root canals may create a physical barrier that inhibits the penetration of sealers into dentinal tubules[30] and lateral canals,[31] and over the long-term it may reduce the sealing capacity of root canal fillings.[32–34] Therefore, $Ca(OH)_2$ remaining in the lateral canals needs to be removed before filling the root canal. LAI may be useful for removing $Ca(OH)_2$ from the lateral canals, however, limited reports have analyzed its removing efficacy.

Therefore, This study aimed to examine the effects of tip insertion depth on the ability of LAI using an Er:YAG laser in removing $Ca(OH)_2$ from the lateral canals compared to UAI. The second aim was to examine the effect of irradiation parameters on the $Ca(OH)_2$ removal efficacy of LAI from the lateral canals. The null hypothesis was that the root canal irrigation method, laser tip insertion depth, and irradiation parameters would have no effect on the removal of $Ca(OH)_2$ from the lateral canals.

Materials and methods

An Er:YAG laser unit (Erwin AdvErl Unit, Morita Manufacturing, Kyoto, Japan) [wavelength 2.94 μm, pulse energy 30–350 mJ, pulse frequency 1, 3.3, 5, 10, 20 and 25 pulses per second (pps), pulse width 200 μsec] was used. Table 1 shows the irradiation conditions and settings of the laser used in this study.

The $Ca(OH)_2$ removing efficacy was evaluated in 192 J-type plastic root canal models (Thermafil Training Bloc, Dentsply Sirona, Ballaigues, Switzerland, #30/0.04 taper, 16.75 mm canal length) with a lateral canal 6 mm from the root apex. A radiopaque $Ca(OH)_2$ paste (Calcipex II, Nippon

Table 1 The parameters and settings in this study.

Manufacturer	Morita Manufacturing, Kyoto, Japan
Model identifier	MEY-1-A
Laser system	Erbium YAG laser
Wavelength	2940 nm
Energy density per pulse (output energy)	30, 70 mJ (11, 26 mJ)
Pulse mode	10, 20 pulses per second (Hz)
Pulse duration	200 μs
Exposure duration of each laser-activated irrigation	20 s
Probe	R200T (0.2 mm diameter), R600T (0.6 mm) conical end (Morita Manufacturing)
Placement of the tip	6, 8, 10, 12, 14 mm from the bottom of root canal model
Application technique	Stationary

Shika Yakuhin, Shimonoseki, Japan; 24% $Ca(OH)_2$, 24% $BaSO_4$, 52% purified water and thickener) was injected into the lateral canal and kept for 1 week at 37 °C and 100% humidity before conducting the experiment.

Experiment 1: effects of root canal irrigation method and tip insertion depth on $Ca(OH)_2$ removal

The models were randomly divided into LAI and UAI groups, which were further divided into 5 subgroups based on tip insertion depth (n = 12 in each group). The tips were positioned at "-8 (8 mm coronal to the height of the lateral canal)", "-6", "-4", "-2", and lateral canal location, i.e., "0" (mm) (Fig. 1).

For LAI, an R200T tip ($\varphi = 200\,\mu m$; Morita Manufacturing) was used for irradiation into the root canal, fixing the tip at relevant depths in the root canal filled with purified water and irradiating 3 times for 20 s each. The irradiation conditions were 30 mJ and 10 pps.

For UAI, an ultrasonic device (Osada ENAC, OE-11 W; Osada, Tokyo, Japan) and a stainless-steel tip (SC4 tip, 19 mm, $\varphi = 200\,\mu m$; Osada) were used at setting 3 (maximum for the tip according to the manufacturer: 30 kHz, 3.6 W). The tip was fixed at relevant depths in the root canal filled with purified water, and irradiation was performed 3 times for 20 s each.

Experiment 2: effect of laser irradiation conditions on $Ca(OH)_2$ removal

Using the same model as in experiment 1, the tip was positioned 8 mm from the lateral canal (position "-8"), and LAI was performed under the following conditions with the root canal filled with purified water (n = 12 in each group). In all cases, irrigation was performed 3 times for 20 s.

(1) Laser output: 30 mJ, 10 pps or 20 pps, tip: R200T
(2) Laser output: 30 mJ or 70 mJ, 10 pps, tip: R200T
(3) Laser output: 30 mJ, 10 pps, tip: R200T or R600T ($\varphi = 600\,\mu m$; Morita Manufacturing).

Micro-computed tomography imaging and $Ca(OH)_2$ volume measurement

Micro-computed tomography (micro-CT; inspeXio SMX-100CT, Shimadzu, Tokyo, Japan) was performed before and after irrigation at 70 kV, 30 μA, voxel size 8.6 μm, 360° around the vertical axis, and 600 views. The volume of

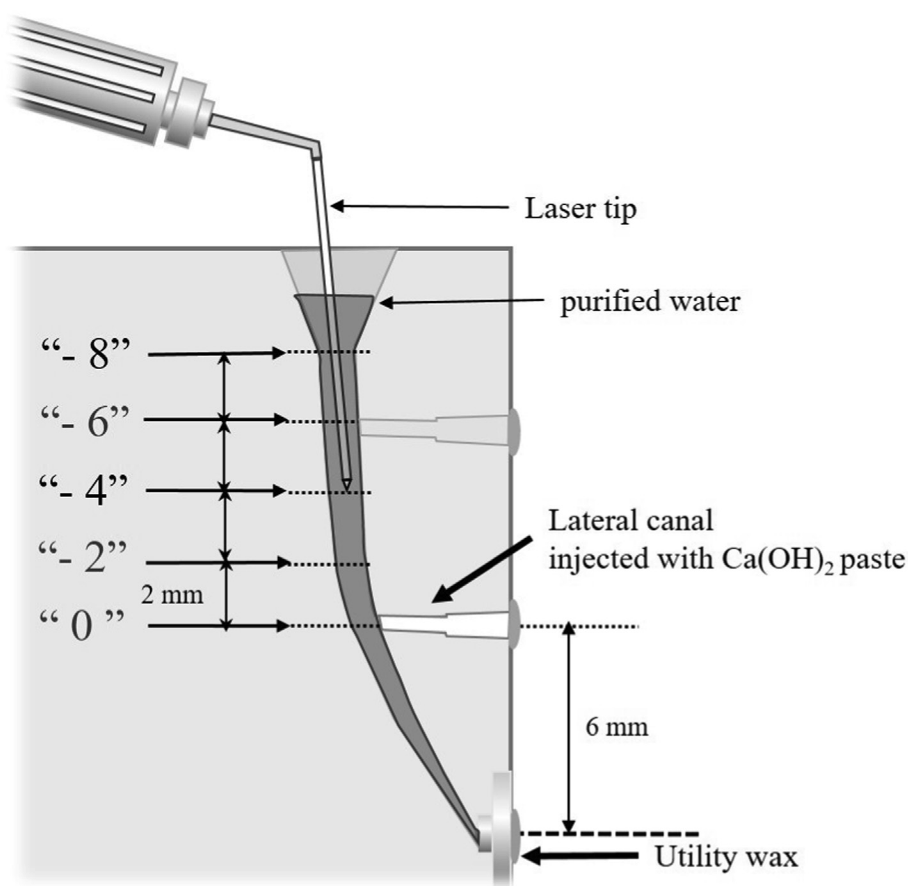

Figure 1 Diagrammatic representation of the experimental setup. $Ca(OH)_2$ paste was injected into the lateral canal. The tip is positioned at each height.

$Ca(OH)_2$ (mm^3) was determined using TRI/3D-BON software (Ratoc System Engineering, Tokyo, Japan), and the $Ca(OH)_2$ removal rate was calculated as follows: $Ca(OH)_2$ removal rate (%) = [1 - $Ca(OH)_2$ volume after irrigation/$Ca(OH)_2$ volume before irrigation] × 100.

Statistical analysis

The SPSS software (IBM SPSS Statistics for Windows, Version 23.0, IBM, Armonk, NY, USA) was used. The Kruskal–Wallis test and Mann–Whitney *U*-test with Bonferroni correction were used to compare the $Ca(OH)_2$ removal rates among different tip insertion depths in each irrigation group. The Mann–Whitney *U*-test was used to compare two independent groups. The significance level was 5%.

Results

Experiment 1

Table 2 shows the median $Ca(OH)_2$ removal rates with LAI and UAI. The tip insertion depth "-8" in LAI showed significantly lower $Ca(OH)_2$ removal rate than depth "-4" ($P < 0.05$). LAI exhibited significantly higher removal rates than UAI at all insertion depths ($P < 0.05$).

Experiment 2

The depth "-8" was chosen since the removing efficacy was the minimum at this depth in experiment 1. When the R200T tip was used, the $Ca(OH)_2$ removal rate was not significantly different between the 30 mJ/20 pps and 30 mJ/10 pps groups ($P > 0.05$; Fig. 2); however, the removal rate was significantly higher in the 70 mJ/10 pps group than that in the 30 mJ/10 pps group ($P < 0.05$; Fig. 3). When irradiation was performed at 30 mJ/10 pps, the R600T tip exhibited a significantly higher $Ca(OH)_2$ removal rate than the R200T ($P < 0.05$; Fig. 4).

Table 2 The median and interquartile range (IQR) of $Ca(OH)_2$ removal rates with LAI and UAI with different tip positions.

Tip position	LAI (%)		UAI (%)	
	Median	IQR	Median	IQR
−8	33.31[A*]	19.69	7.09[a]	17.09
−6	53.57[AB*]	76.78	12.84[a]	25.36
−4	100.00[B*]	9.49	19.68[a]	24.37
−2	96.84[AB*]	26.36	52.55[a]	51.41
0	94.91[AB*]	15.61	25.70[a]	69.43

Different capital and lower-case letters indicate significant pairwise differences between different tip positions in LAI and UAI, respectively (Kruskal–Wallis test followed by Mann–Whitney U-test with Bonferroni correction, $P < 0.05$). * Statistically significant differences between LAI and UAI (Mann–Whitney U-test, $P < 0.05$). N = 12 per group.
LAI tip position "-8" had a significantly lower $Ca(OH)^2$ removal rate than position "-4" ($P < 0.05$). LAI exhibited significantly higher removal rates than UAI at all positions ($P < 0.05$).

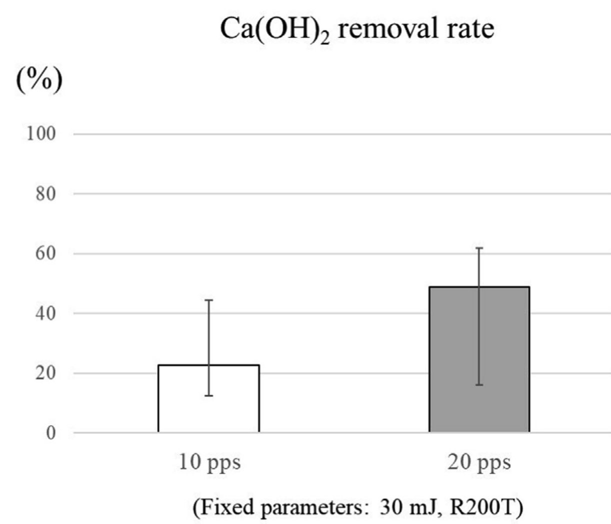

Figure 2 Effect of pulse frequency on $Ca(OH)_2$ removal rates with the tip in position "-8". Data represent the median and the interquartile range; n = 12 per group. There was no significant difference between each pulse frequency ($P > 0.05$).

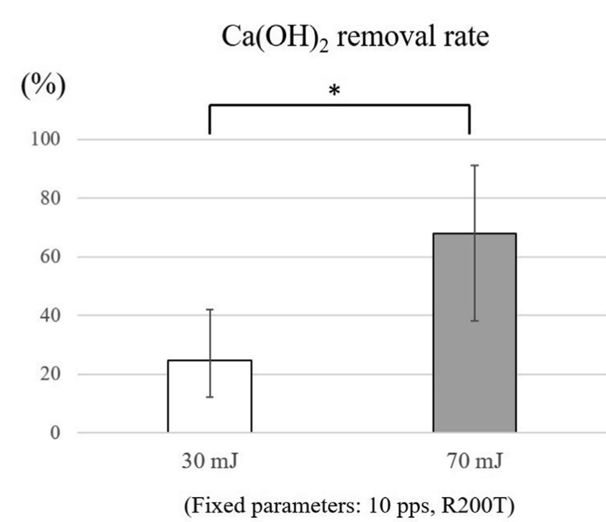

Figure 3 Effect of pulse energy on $Ca(OH)_2$ removal rates with the tip in position "-8". Data represent the median and the interquartile range; n = 12 per group. * Statistically significant difference (Mann–Whitney *U*-test with Bonferroni correction, $P < 0.05$).

Discussion

LAI improves root canal cleaning through cavitation, increased fluid flow, and shock waves created by the rapid generation and collapse of vaporized bubbles, which activate the irrigant.[10,14] This study compared the efficacy of LAI in removing $Ca(OH)_2$ in lateral canals with that of UAI, and found that the removing efficacy of LAI was significantly better, even with the laser tip positioned away from the cleaning site. Previous studies examined the cleaning of lateral canals in either extracted teeth or root canal models filled with a dye, hydrogel mimicking biofilm, bovine pulp,

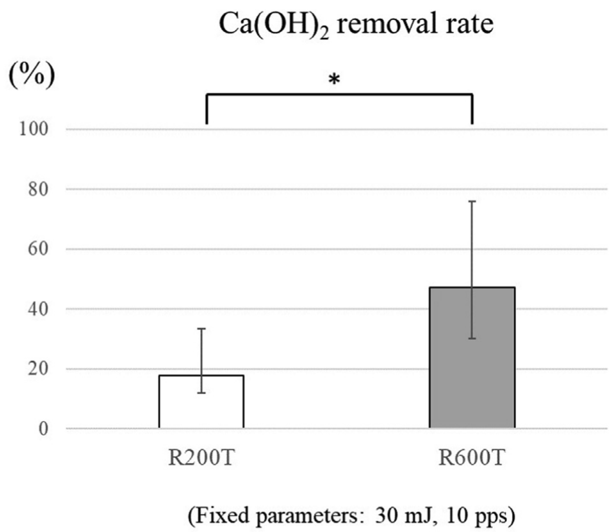

Figure 4 Effect of tip diameter on $Ca(OH)_2$ removal rates with the tip in position "-8". Data represent the median and the interquartile range; n = 12 per group. * Statistically significant difference (Mann–Whitney *U*-test with Bonferroni correction, $P < 0.05$).

or other substances in two-dimensional images.[11,12,35,36] To ensure accuracy and reproducibility, the present study performed non-destructive three-dimensional analysis using micro-CT. Radiopaque $Ca(OH)_2$ paste was used as an indicator for comparing the root canal cleaning efficacy.

The present results showed that LAI was significantly more efficient than UAI in removing $Ca(OH)_2$ paste from lateral root canals. Cavitation and acoustic streaming is a common phenomenon in both LAI and UAI.[10,20] With LAI, the high absorption rate of the Er:YAG laser rapidly heats the water; this leads to the generation and collapse of vaporized bubbles, which creates shock waves and a high fluid flow, resulting in photon-induced photoacoustic streaming in front of the tip.[10] With UAI, the vibration of the ultrasonic file itself generates acoustic flow around the file.[20] The difference in these mechanisms is presumed as the cause for differing efficacies between LAI and UAI.

The present finding that LAI with the tip away from the lateral canal exhibited a similar or higher cleaning efficacy than UAI with the tip close to the lateral canal is consistent with previous studies.[9,15–17,19,20,37] However, when the tip is close to the root canal orifice, LAI is less capable of removing debris from artificial grooves in the root canals of extracted teeth, and of cleaning the smear layer around the root apex.[27,28] Similarly, in this study, the cleaning efficacy decreased when the tip was located 8 mm away from the lateral canal.

However, increasing the tip insertion depth and output of the laser can increase both irrigant extrusion and pressure outside the apical foramen.[21–26] Thus, in terms of safety, LAI should be performed by placing the tip in the coronal part of the root canal and selecting a suitable output.

In experiment 2, a tip insertion depth that showed reduced cleaning efficacy in experiment 1 was used to investigate the irradiation conditions that would improve cleaning of lateral canals. The results showed that, while increasing the pulse frequency did not significantly affect cleaning, increasing the irradiation energy improved cleaning of the lateral canals away from the tip. This is consistent with a previous study that found no significant differences in cleaning between the pulse frequencies used in this study (10 and 20 pps).[27] Increasing the pulse frequency increases the number of irradiations per unit of time and creates more micro-explosions and an increased fluid flow, which is thought to improve cleaning around the tip. However, when low energy irradiation is used, the energy available for agitating the irrigant in distal areas is reduced. The water flow kinetics in various root canal regions at different distances from the tip should be investigated in detail in future studies.

Under the present experimental conditions, larger diameter laser tips increased $Ca(OH)_2$ removal. One study found that increasing the tip diameter generated more vaporized bubbles when LAI was performed in restricted environments than in spacious ones.[14] In addition, the present results are similar to those of another study,[26] which found that increasing the tip diameter increased the number of vaporized bubbles and pressure outside the apical foramen. This is probably because thicker tips restrict the movement of vaporized bubbles along the length of the root canal, which creates the formation and destruction of vaporized bubbles that contributes to the cleaning efficacy. In contrast, another study found that the ability of LAI to clean root canals was not significantly influenced by tip diameter;[27] this could be attributed to the thinner tips used in this study. Moreover, increasing the tip diameter creates a more closed environment inside the root canal, which could either lead to direct laser irradiation of the root canal due to the depletion of the irrigant or to decreased distance or direct contact of the tip with the root canal, both of which raise safety concerns. The above indicates a thicker tip should be positioned sufficiently far from the root apex.[38]

LAI exhibited better cleaning efficacy than UAI in lateral canals when positioned away from the opening of the lateral canal, though in these experimental conditions, this efficacy was diminished when the opening of the lateral canal was 8 mm away. However, large tip diameters and increased pulse energies contribute to the cleaning efficacy. Therefore, to ensure cleaning efficiency as well as irradiation safety, if the target object is near the center of the root, it is recommended to perform irradiation with a thin laser tip places at a few mm coronal to the object. However, if the object is near the root apex, it is recommended to use a large diameter tip placed as far as possible from the object, adjusting the irradiation output to ensure safety and improve LAI efficacy.

In this study, purified water was used as the irrigant, based on reports that cleaning efficiency and laser absorption efficiency do not differ significantly between sodium hypochlorite and water,[39] and that sodium hypochlorite and water show similar abilities of removing $Ca(OH)_2$ from the root canals.[40] However, other irrigants such as EDTA may exhibit different cleaning behavior. Further, while this study used simulated lateral canals (diameter 400 μm) in plastic models, actual lateral canals are thinner than these models (diameter < 200 μm) and differences between the model material and root canal walls could affect the kinetics of the irrigant. Therefore, care should be taken when extrapolating these results to clinical conditions. To optimize the clinical application of LAI, further studies analyzing its cleaning efficacy and safety are needed.

Although none of the methods could completely remove $Ca(OH)_2$ from the lateral canals, LAI using Er:YAG laser exhibited significantly higher cleaning efficacy than UAI with the tip placed away from the opening of the lateral canal. In addition, while increasing pulse frequency did not improve the ability of LAI to remove $Ca(OH)_2$, significant improvement was observed by increasing the pulse energy and tip diameter.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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