Evaluation of cleaning efficacy-related properties of root canal irrigant activation using a computer-controlled hot tip powered with a diode laser

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Purpose: This study aimed to examine root canal irrigant activation using a computer-controlled hot tip (thermo-optically powered [TOP] tip) heated with a 980 nm diode laser system (Alta Modular Laser System), with regard to vaporized bubble formation and soft tissue dissolution capacity.
Materials and Methods: As a parameter of cleaning efficacy, the number and size of vaporized bubbles generated in root canal models during TOP tip-induced activation were analyzed with high-speed digital video imaging. To evaluate the soft tissue-dissolving efficacy of TOP tip-induced activation with a sodium hypochlorite irrigant, dissolution of porcine soft tissues filled in lateral canals set at two levels in root canal models were morphometrically analyzed. Irrigant temperature during TOP tip-induced activation was measured with thermocouples attached to the apical foramen and the lateral canals of root canal models.
Results: High-speed video imaging revealed that TOP tip-induced activation of the water that filled the root canal models, required less time to achieve the first bubble formation and generated a larger number of bubbles than a normal clear tip-induced activation using the same laser. NaOCl solution activated with TOP tip dissolved more soft tissues filled in lateral canals of the canal models, than with passive ultrasonic irrigation and syringe irrigation. Irrigant temperature during TOP tip-induced activation showed a maximum increase of approximately 50˚C near the lateral canal, as measured with thermocouples.
Conclusion: Under the present experimental conditions, TOP tip-induced irrigant activation exerted better cleaning efficacy-related properties than the other methods tested.

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Key Words: diode laser, hot tip, irrigant activation

Introduction

Intracanal pathogens, such as necrotic soft tissue remnants and microorganisms, are the primary cause of apical periodontitis. To eradicate the pathogens, root canal treatment is conducted via a combination of mechanical instrumentation and root canal irrigation. However, complete elimination is challenging due to the presence of complex root canal structures that do not allow effective debridement, such as lateral canals, fins, isthmuses and apical ramifications [1,2]. Thus, improvement of root canal cleaning procedures, aimed at more effective removal of intracanal pathogens, is of significant importance to elevate the predictability of root canal treatment.

Mechanical instrumentation allows for the access of only 40-80% of the root canal area [1,3]. Therefore, root canal irrigation serves as a critical procedure to facilitate the elimination of intracanal pathogens that are left in the uninstrumented area [1,3]. Sodium hypochlorite (NaOCl) is a root canal irrigant of choice due to its effective antimicrobial and organic tissue-dissolving capacities [4]. Hand irrigation using a syringe and a needle (syringe irrigation; SI) is employed routinely, although it has limited effectiveness in the apical portion as well as the complexities of the root canal [4]. To enhance irrigation efficacy, sonic and ultrasonic activation have been employed [5].

Laser-activated irrigation (LAI) has gained attention for its potential to efficiently clean the root canal system. LAI exerts improved efficacy through generation of cavitation bubbles, high-velocity water flow, and shock waves [6], and is similarly or significantly more effective in cleaning the root canal system compared with hand irrigation and ultrasonic irrigation [7-9]. Moreover, LAI with NaOCl has been reported as significantly more effective than conventional irrigation techniques for soft tissue dissolution [10,11]. Several kinds of lasers have been reported to achieve the laser-induced cavitation and streaming effect, including erbium chromium, yttrium scandium gallium garnet (Er,Cr:YSGG) [6,7], erbium-doped yttrium aluminum garnet (Er:YAG) [7-9], neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers [12], and diode lasers at 940 and 980 nm wavelengths [13,14].

A "hot tip" or "laser-activated thermal probe" that transforms the laser energy into thermal energy is widely employed in various laser-assisted surgeries, and is formed by adhesion of certain flammable materials to the distal end of the laser tip, such as tissue fragments, paper, wood, and carbon materials as an optical-thermal converter [15,16]. A diode laser with a 970 nm wavelength and carbon-coated hot tip activation in water was reported to exert hydrodynamic effects; it generates vaporized bubbles and high-speed streaming up to 100 mm/s resulting from explosive boiling [17,18].

Recently, a novel 980 nm diode laser, the Alta Modular Laser System (Alta MLS; Dental Photonics, Walpole, MA, USA), featuring a system to create a computer-controlled hot tip (thermo-optically powered tip: TOP tip), was developed [15]. Studies have reported its efficacy in soft tissue operations and a reduction of thermal collateral damage to the surrounding tissues compared with the performance of a normal clear tip [15,16]. In this system, the distal end of the cylindrical quartz glass fiber tip is converted into a highly light-absorbent particle-impregnated layer with a computer-controlled initiation process to achieve a consistent hot tip. The fiber tip is first pressed into a carbon-based target and activated at a preset power level, resulting in the deposition of particles onto the distal end of the fiber tip. The TOP tip emits incandescent thermal radiation heating to 500-1,200˚C at 1,400-11,000 nm broadband wavelength, which differs from a laser [15].

Application of the Alta MLS with a TOP tip-induced irrigant activation may have potential clinical benefits, since the system may induce rapid heating of irrigants, resulting in efficient vaporized bubble formation and high-temperature water streaming. However, the root canal cleaning efficacy of this system when used for irrigant activation has not yet been investigated. Thus, the aim of this study was to examine TOP tip-induced irrigant activation with regard to selected properties related to cleaning efficacy, i.e., vaporized bubble formation and soft tissue dissolution capacity.

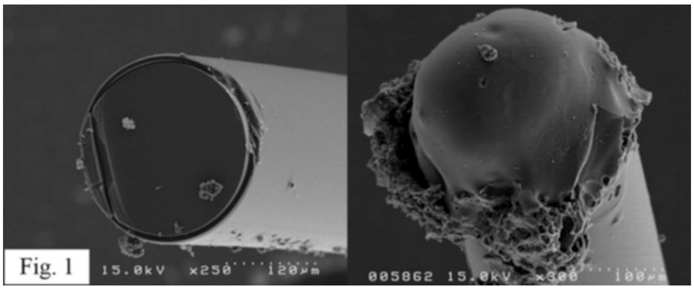
Materials and Methods

Experiment 1: Evaluation of TOP tip-induced vaporized bubbles with high-speed digital video imaging

First, generation and kinetics of vaporized bubbles during root canal irrigation were examined as parameters of cleaning efficacy; the time taken to the first bubble formation and number of bubbles were measured. Twenty-one plastic root canal models with lateral branches (Thermafil Training Bloc #1, apical diameter 0.30 mm, 0.04 taper; Dentsply Sirona, Ballaigues, Switzerland) were used. These models simulated lateral canals located 6 and 12 mm from the apical foramen. Distilled water, rather than NaOCl solution, was used as the irrigant to protect the experimental devices. It has been reported that the light transmission spectrum of NaOCl solution follows the spectrum of water to a large extent [19].

The samples used were divided into 3 groups (n = 7, each). In Group Clear, the Alta MLS (Fig. 1) was used at 2 W (45 mJ, 44 pps) with a normal "clear tip" formed as a result of a mechanical cleave (DS1-200, Dental Photonics). In Group TOP, the Alta MLS with a TOP tip converted from the DS1-200 tip, which emits thermal radiation, was used at 2 W (45 mJ, 44 pps). A group without laser irradiation served as the control group. After filling the root canal with distilled water, the laser tip was positioned 9 mm from the apical foramen and irradiation was performed seven times for 10 s each.

Vaporized bubbles in the distilled water were recorded with a high-speed camera (VW-9000, Keyence, Osaka, Japan). The frame rate and the exposure time were set at 1,000 fps and 1/3,000 s, respectively. The camera was placed horizontally at a distance of 28 mm from the sample at 75× magnification. The time taken from commencement of irradiation to the first bubble formation and number of bubbles on the captured images were analyzed with video analysis software (VW-9000 Motion Analyzer 1.4.0.0, Keyence) at every 0.1 s for 5 s. The first moment of irradiation was designated as 0 s.



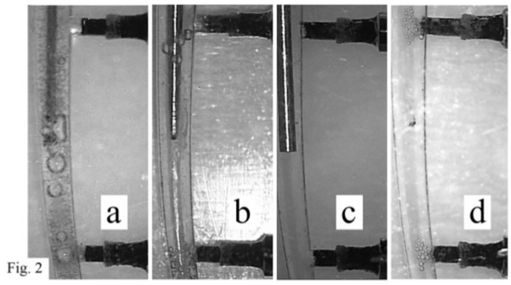


Fig. 1 Scanning electron microscope images of the clear tip (a cylindrical fiber tip; left) and the TOP tip (right)
Fig. 2 Representative images showing porcine soft tissues (black) remaining during TOP tip-induced irrigant activation (a), PUI (b), SI (c), and control (d)

Experiment 2: Soft tissue-dissolution during irrigant activation

This experiment was conducted to examine whether the TOP tip-induced cavitation and streaming effect is capable of enhancing the soft tissue dissolution capacity of NaOCl solution compared with passive ultrasonic irrigation (PUI) and syringe irrigation (SI). Twenty-eight plastic root canal models, identical to those used in Experiment 1, were used. The samples used were divided into 4 groups (n = 7, each). Porcine soft tissue stained with a 1.0% methylene blue solution to aid visualization was packed into each lateral canal. An NaOCl solution (6%, Dental Antiformin, Nippon Shika Yakuhin, Shimonoseki, Japan) was used as the irrigant.

In Group TOP, the Alta MLS set to 2 W (120 mJ, 16 pps) with the TOP tip converted from the DS1-200 tip was used. After filling the root canal with the NaOCl solution, the tip was positioned 9 mm from the apical foramen and activated three times for 20 s each (i.e., 60 s). In passive ultrasonic irrigation (Group PUI), the ENAC SE10 ultrasonic system (Osada, Tokyo, Japan, 30 kHz) with an ultrasonic tip (SC4, Osada) was used. After filling the root canal with the NaOCl solution, the tip was positioned 9 mm from the apical foramen and activated at the highest power within the recommended setting range by the manufacturer for the tip (setting: 3, 5.6 W) three times for 20 s each (i.e., 60 s). Conventional syringe irrigation (Group SI) was conducted with a syringe (Nipro Syringe; Nipro, Osaka, Japan) and a 27-gauge (ø 0.40 mm) irrigation needle (Nipro Blunt Needle, Nipro). After filling the root canal with the NaOCl solution, the needle tip was positioned at 9 mm from the apical foramen and 1 mL of the irrigant was delivered manually for 20 s, three times (i.e., 60 s). In the control group, the NaOCl solution was left stationary for 60 s.

Following the irrigation with NaOCl solution, the root canals were irrigated with 1 mL of distilled water and dried with paper points. All procedures were recorded with a dental operating microscope (OPMI Pico with MORA interface, Carl Zeiss, Oberkochen, Germany) equipped with a digital video recorder (DATA Gen PRO for Dental; Seventh Dimension Design, Kobe, Japan) at a 21.3× magnification (Fig. 2). Captured images were analyzed for dissolved soft tissue area before and after the experiment via image analysis software (Photoshop CS5; Adobe, San Jose, CA, USA), according to the method described in a previous study [10].

Experiment 3: Measurement of the irrigant temperature during TOP tip-induced irrigant activation

To examine whether TOP tip-induced irrigant activation exerts thermal effects related to the cleaning efficacy, irrigant temperature rise was measured during the activation. Plastic root canal models identical to those used in Experiment 1 were used. Three K-type thermo-couples (ø 0.15 mm, Okazaki, Kobe, Japan) were inserted into the canal through the apical foramen and the simulated lateral canals, and set at 2, 6, and 12 mm from the apical foramen (Fig. 3). Distilled water was used as an irrigant and experiments were done in a thermostat air box maintained at 37°C. The TOP tip was positioned at 10 mm from the apical foramen and activated as in Experiment 2, and the irradiation was repeated 7 times for 20 s. Temperature changes were recorded continuously in real-time with a recording device (NR-1000, Keyence) and data logging software (Wave Thermo 1000, Keyence) with a 0.1-s sampling interval.

Statistical analyses

Statistical analyses for all experimental results were performed using one-way analysis of variance (ANOVA) and the Tukey-Kramer post-hoc test. Significance was set to 5% for all analyses.

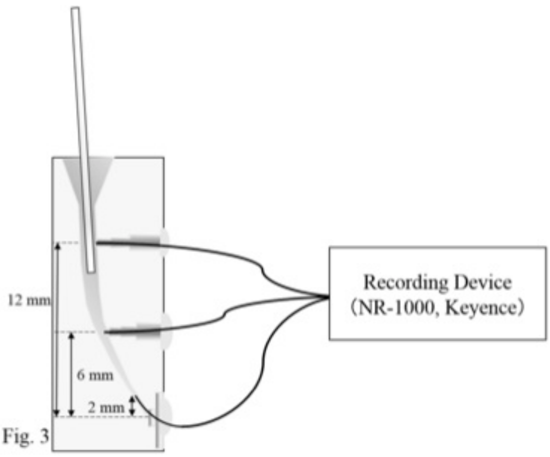


Fig. 3

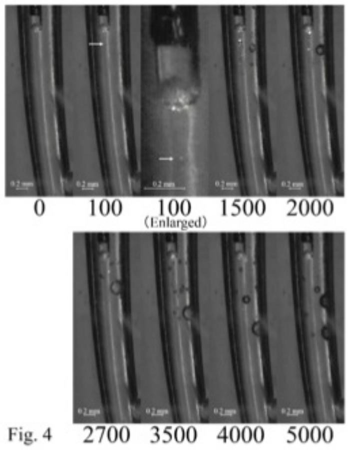


Fig. 4

Fig. 3 Schematic diagram of the setup for Experiment 3. Three K-type thermo-couples were inserted into the canal through the apex and the lateral canals of the root canal model, and positioned at 2, 6, and 12 mm from the apical foramen.

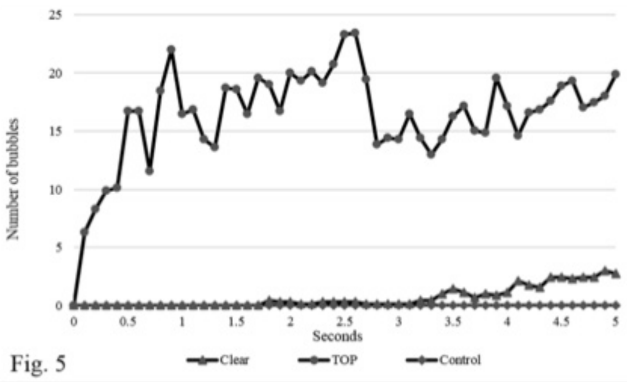
Fig. 4 Representative images showing bubbles generated in the root canal model during TOP tip-induced irrigant activation. Numbers show the time (μs) from the onset of the laser-pulse. The arrow shows the first bubble after irradiation.

Results

Representative high-speed camera images of the TOP group are shown in Fig. 4. As shown in Fig. 5, the mean number of bubbles detected in the TOP groups was significantly greater than that in the Clear and control groups ($p < 0.05$). In addition, observable bubbles in the TOP group appeared significantly faster than those in the Clear group ($p < 0.05$). It took 191 ± 44 and 3,549 ± 2,060 ms to detect observable bubbles in the TOP and Clear groups, respectively. No bubbles were observed within 5 s in the control group (Fig. 5).

The results of soft tissue-dissolution during irrigation are shown in Fig. 6. In the lateral canal at the 12 mm level, the TOP and PUI groups showed significantly larger areas of dissolution than the other groups ($p < 0.05$; Fig. 6, upper panel). In the lateral canal at the 6 mm level, however, the TOP group exhibited a significantly larger area than the other groups (p < 0.05; Fig. 6, lower panel).

The mean maximum temperature rise of the irrigant by location during TOP tip-induced irrigant activation corresponded to 12 mm > 6 mm > 2 mm (p < 0.05; Fig. 7). An approximately 50˚C increase in temperature was detected at the 12 mm level (2 mm from the laser tip).



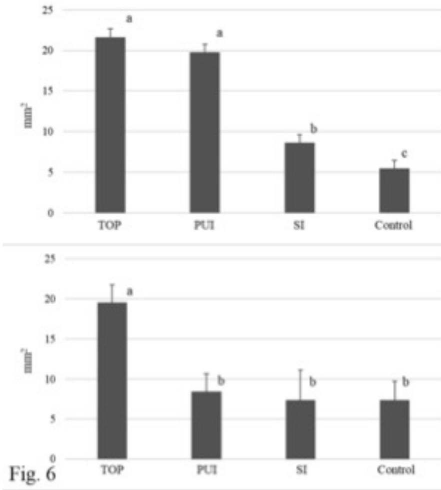


Fig. 5 Time-course changes (upper panel) and means (lower panel) in the number of bubbles formed during irrigant activation. *n* = 7 in each group. Different letters indicate statistically significant differences (*p* < 0.05).
Fig. 6 (Upper panel) Average of dissolved tissue area at the lateral canal positioned 12 mm from the apical foramen during each irrigation. (Lower panel) The average of dissolved tissue area at the lateral canal positioned 6 mm from the apical foramen during each irrigation. Different letters indicate statistically significant differences (*p* < 0.05).

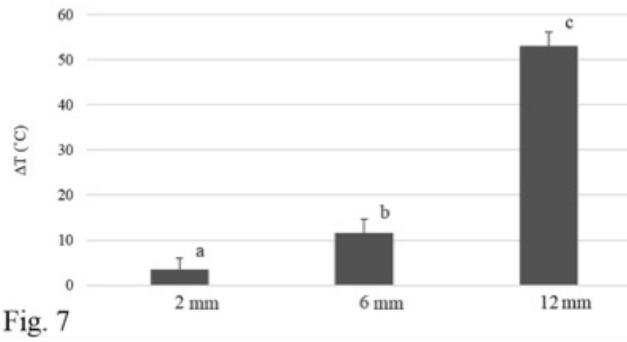


Fig. 7
Means of the maximum temperature rise of the irrigant at different levels from the apex (0 mm) during TOP tip-induced irrigant activation. *n* = 7.
Different letters indicate statistically significant differences (*p* < 0.05).

Discussion

The mechanism underlying the TOP tip involves the fast conversion of laser energy into thermal energy at the surface of the distal end of the fiber tip, which contains a thin, light absorbing layer as a hot tip. The distal end of the TOP tip heated to 500-1,200˚C emits thermal radiation [15]. As a consequence, it can rapidly boil the water around the distal end of the tip, resulting in evaporation and bubble formation. The water absorption property of each wavelength is also associated with the generation of bubbles in the root canal and subsequent water streaming [6,8,9,13,14,19,20]. The values of absorption into water of 980 nm wavelengths are relatively small (0.243) [19]. This fact explains the results of Experiment 1, in which only a few bubbles were observed in the 980 nm diode laser (Clear) group. In the present study, it took about 3 s in the 980 nm diode laser (Clear) group to acquire observable bubbles. This is consistent with earlier studies showing that a 980 nm diode laser (Sirolaser, Sirona, Bensheim, Germany) can generate cavitation bubbles within 5 s after irradiation at 2.5 W, 25 pps [13] or about 13 s after irradiation at 2 W, 20 pps [14]. In contrast, the TOP group required significantly shorter time (only 0.2 s) until initial bubble formation and generated significantly more bubbles compared with the Clear group. These findings clearly indicate that the TOP tip is more efficient in heating water to generate vaporized bubbles and is different from diode laser-induced activation. Since the generation of bubbles gives rise to the circulation of liquid [17,18], TOP tip-induced irrigant activation may be beneficial in improving root canal cleaning efficacy.

In Experiment 2, we demonstrated that the amount of soft tissue dissolution by the TOP group was similar at 12 mm and higher at 6 mm compared with the results obtained with PUI (Fig. 6), indicating that the TOP group was more effective than PUI over a longer distance. It has been reported that LAI with the tip at 5 mm from the apical foramen removes dentin debris plugs as efficiently as PUI with the tip at 1 mm [9]. Our results of TOP tip-induced irrigant activation were similar, supporting the notion that laser-induced cavitation and streaming cleans the root canal over a longer distance from the tip than PUI. In other words, shallower insertion depths during TOP tip-induced irrigant activation may be sufficient.

Among several factors that influence soft tissue dissolution rates, including irrigant concentration, temperature, agitation, and surfactant factors [21], temperature rise may have some influence on the difference between TOP and PUI. Regarding the effects of temperature rise when NaOCl irrigant is used, it has been reported that the dissolved tissue rate for 1.0% NaOCl solution heated at 60˚C is significantly higher than that for 5.25% NaOCl solution at 20˚C, and that the rate reached a plateau when the temperature was 60˚C [22]. Moreover, bactericidal rates for NaOCl solution may more than double for each 5 degrees rise in temperature in the range of 5 to 60˚C [23]. As demonstrated in Experiment 2, the TOP tip-induced irrigant activation may have an irrigant heating ability sufficient to enhance its cleaning efficacy; in the present study, the mean maximum irrigant temperature rise during TOP tip-induced irrigant activation was largest at the 12 mm level (2 mm from the laser tip), where approximately 50˚C of temperature rise was detected (Fig. 7).

While root canal treatment with a laser may offer therapeutic benefits, careful consideration of potential complications, including irrigant extrusion outside the apical foramen [9] and thermal damage to the periradicular tissues [24,25], is required. In particular, apical extrusion of NaOCl solution can cause severe damage to the periradicular tissues [26-28]. As for thermal side-effects, excessive temperature increases on the root surface can cause irreversible bone and periodontal ligament damage as well as dehydration effects to dentin, resulting in external resorption [24,29]. The safety threshold of the temperature increase is considered to be 7˚C [25]. In this regard, we have preliminarily found that the TOP tip-induced irrigant activation caused root surface temperature increase of less than 7˚C (data not shown), suggesting low risk of thermal damage. However, further investigation on the safety of TOP tip-induced irrigant activation seems necessary.

Under the experimental conditions described in this study, results can be summarized as; (i) TOP tip-induced irrigant activation required less time to produce the first bubble formation and generated a larger number of vaporized bubbles than the normal clear tip-induced irrigant activation using the same 980 nm diode laser; (ii) TOP tip-induced irrigant activation exerted better soft tissue dissolving capacity over a longer distance from the tip than PUI; and (iii) approximately 50˚C of maximum irrigant temperature rise during TOP tip-induced irrigant activation was detected near the lateral canal. Thus, within the limitations of this study, it can be concluded that TOP tip-induced irrigant activation exerted similar or better cleaning efficacy-related properties compared with those of the other irrigation methods tested.

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Conflicts of Interest
The authors declare no conflicts of interest.

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