Determination of Optimal Separation Times for Dual-Pulse SWEEPS Laser-Assisted Irrigation in Different Endodontic Access Cavities

Matjaž Lukač,1 Giovanni Olivi,2 Mihnea Constantin,2 Neje Lukač,3 and Matija Jezeršek, PhD2,3
1Department of Complex Matter, Jožef Stefan Institute, Jamova cesta 39, 1000, Ljubljana, Slovenia
2Master Laser Dentistry, Catholic University of Sacred Hearth-Rome, Largo Francesco Vito, 1, 00168, Rome, Italy
3Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, 1000, Ljubljana, Slovenia

Background and Objectives: The purpose of this *ex vivo* study is to investigate whether it is possible to predictetermine and set the optimal separation times for the SWEEPS Er:YAG laser pulses pair during laser-assisted irrigation of endodontic root canals based on known lateral dimensions of the endodontic access cavities of different types of teeth.

Study Design/Materials and Methods: As the optimal SWEEPS laser pulse pair separation for enhanced shockwave generation depends on the life cycle of a single-pulse bubble, measurements of the oscillation time $T_B$ of the Er:YAG laser-generated bubble were made in 23 different endodontic access cavities of different types of teeth progressively widened in three different steps, into larger cavities, for a total of 69 cavities of different shapes and sizes. Different fiber-tip geometries (flat and radial), laser pulse energies (10 mJ and 20 mJ) and depth of fiber-tip insertion (2 mm and 4 mm) were also investigated. The obtained data were then analyzed using the reported relationship between the bubble oscillation time and the diameter of a cylindrically shaped cavity.

Results: A good fit to the relation analogue for ideal cylindrical cavities was found by taking the characteristic diameter of the access cavity to be represented by the cavity diameter either in the mesiodistal ($D_{min}$) or buccolingual ($D_{max}$) direction, or alternatively by the average of the two diameters ($D_{ave}$). The best fit was obtained for $D_{min}$ ($R^2 = 0.73$) followed in order by $D_{ave}$ ($R^2 = 0.71$) and $D_{max}$ ($R^2 = 0.63$).

Conclusion: In spite of the endodontic cavities being non-cylindrical and of varied shape and size, the bubble oscillation time $T_B$ and the corresponding optimal SWEEPS separation time can be well predicted using a single characteristic dimension of the access cavity. This finding enables a simple and practical method for determining optimal conditions for shock wave generation and enhanced photodynamic streaming in differently shaped and sized root canals, leading to improved treatment efficacy and safety of root canal irrigation. Lasers Surg. Med. © 2020 The Authors. Lasers in Surgery and Medicine published by Wiley Periodicals LLC

Key words: laser-activated irrigation; Er:YAG laser; root canal irrigation; dual-pulse

INTRODUCTION

The root canal preparation consists of mechanical instrumentation followed by chemical irrigation [1–3], which is the most critical stage for the elimination of the infected material from the root canal that includes removal of bacteria, vital, necrotic, and infected tissues [4–7]. Due to the highly complex anatomy of the root canal system [8], the standard method of hand syringe irrigation has been found unsatisfactory for cleaning and disinfecting the root canal wall from debris and bacteria [9,10]. For this reason, various other techniques such as negative pressure [11], sonic [12], and ultrasonic irrigation [13–15], and more recently laser-activated irrigation (LAI), have been introduced to enhance the irrigation action [16–23].

During LAI, short Erbium laser pulses (wavelength: 2.94 µm for Er:YAG and 2.78 µm for Er, Cr:YSGG) with durations in the range of 25–200 µs are delivered through a fiber tip (FT) into the irrigant-filled coronal access cavity. Due to the strong absorption of the Erbium wavelength in the irrigant, a vapor bubble is generated at the end of the submerged fiber tip [26]. The rapid expansion and collapse of the bubble results in secondary cavitation and fluid motion along the entire root canal system [18,27,28] leading to enhanced chemomechanical irrigation [19,29] when ethylenediaminetetraacetic acid and NaOCl solution are used as irritants. This long-distance action of LAI represents

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

Conflict of Interest Disclosures: All authors have completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest and have disclosed the following: Two of the authors (Matjaž Lukač and Neje Lukač) are affiliated also with Fotona, d.o.o.

Correspondence to: Matija Jezeršek, Faculty of Mechanical Engineering, University of Ljubljana, Jamova cesta 39, 1000 Ljubljana, Slovenia. E-mail: matija.jezersek@fs.uni-lj.si

Accepted 7 November 2020
Published online 1 December 2020 in Wiley Online Library (wileyonlinelibrary.com).

DOI 10.1002/lsm.23357

© 2020 The Authors. Lasers in Surgery and Medicine published by Wiley Periodicals LLC
The bubble oscillation time on the diameter of water-filled cylindrically shaped cavities [38]. A method for determining optimal separation times for typical cavity dimensions, fiber tip geometries and laser pulse energies is proposed.

MATERIALS AND METHODS

Experimental Setup

Twenty-three human teeth (eight upper and three lower molars, two upper and one lower premolars, two upper canines and three upper and four lower incisors) extracted for periodontal and/or orthodontic reasons were used in the study. Informed consent to the scientific use of the extracted teeth was signed by all the patients.

Endodontic access cavities were prepared in all extracted teeth using a round diamond bur. A specific shape of the access cavity was performed for each different tooth type. In order to simulate differently sized access cavities, as encountered in clinical practice. The access cavities were first minimally prepared, and then in two additional stages progressively widened into larger cavities. Thus, altogether, 3 × 23 differently sized and shaped access cavities were obtained and evaluated. The dimensions of the lateral side of the access cavities, prepared during each stage, were determined by measuring the mesiodistal (minor: \(D_{\text{min}}\)) and buccolingual (major: \(D_{\text{max}}\)) sides of the access cavity of each prepared anterior and posterior tooth (see Fig. 1a) using a microscope. The range of average diameters \(D_{\text{ave}} = (D_{\text{min}} + D_{\text{max}})/2\) varied from 1.2
to 3.6 mm for the first preparation stage, from 1.86 to 4.32 mm for the second preparation stage, and from 2.13 to 6.18 mm for the last preparation stage. Note that repeated experiments on the same tooth do not influence the results as the LAI cleaning effects have a negligible effect on the size and shape of the access cavity where the bubble oscillation times were measured.

The prepared teeth were submerged in a water reservoir, and LAI was performed using an Er:YAG laser (LightWalker, Fotona d.o.o., Slovenia) equipped with a dental handpiece (H14, Fotona d.o.o., Slovenia) optically coupled with an interchangeable FT. The handpiece air/water spray was turned off during all experiments. The following FTs (manufactured by Fotona) were used in the study [35]:

1) Flat fiber tip; cylindrical flat-ended FT with 400 µm diameter (Flat Sweeps400, Fotona d.o.o., Slovenia).
2) Radial fiber tip; cylindrical radially-ended FT with 400 µm diameter (Radial Sweeps400, Fotona d.o.o., Slovenia).

The laser FT’s end was positioned at two different depths in the access cavity, \( h = 2 \) or \( h = 4 \) mm (see Fig. 1b), using an XYZ micrometer positioning stage. The FT’s position relative to the canal was monitored with a digital camera (Chameleon3, 1.3 MP; PointGrey, Richmond, Canada) with the optical resolution of 0.1 mm.

The bubble oscillation time was measured by “listening” to the sound of the explosive growth and collapse of the bubble using a microphone (Brüel & Kjær, Type 2669, Nærum, Denmark) positioned outside of the water reservoir. A typical signal is shown in Figure 2. As the X-SWEEPS pulse pair consists of two ultra short pulse (USP) laser pulses with duration of \( t_p \approx 25 \mu s \), the oscillation time of the primary bubble generated by the first pulse of the SWEEPS pulse pair was determined by measuring the oscillation time \( T_B \) of a single USP pulse. Single USP laser pulse energies of \( E_L = 10 \) mJ and 20 mJ were used.

Measurements were made for each endodontic access cavity geometry and laser activation condition (FT type, \( E_L \), and \( h \)).

**Data Analysis**

Recently [38], it was shown that for long liquid-filled cylindrical cavities (i.e., tubes) with diameter \( D_{\text{cavity}} \), the bubble oscillation time \( T_B \) can be well described by a function:

\[
T_B = T_{B,\inf}(1 + K/D_{\text{cavity}})
\]

where \( K \) is the fitting parameter and \( T_{B,\inf} \) is the bubble oscillation time in an infinite reservoir \( (D_{\text{cavity}} \approx \infty) \) for a particular set of laser and FT parameters. The ratio \( T_B/T_{B,\inf} \) was found to be independent of the laser pulse energy \( E_L \), with the best fit obtained for \( K = 3.52 \) mm where the statistical coefficient of determination \( R^2 = 0.96 \).

Even though endodontic access cavities are relatively shallow and not cylindrically shaped, it was assumed that the access cavity bubble oscillation data can be approximated by a function similar to that in Equation (1):

\[
T_B = T_{B,\inf}(1 + K/D_i)
\]

where \( D_i \) represents one of the main lateral dimensions of the access cavity, \( D_{\text{min}}, D_{\text{max}} \) or \( D_{\text{ave}}, \) and \( K_{\text{min}}, K_{\text{max}} \) and \( K_{\text{ave}} \) are the corresponding fitting parameters. The time
**RESULTS**

Figure 3 shows the measured dependence of the bubble oscillation time \( T_B \) on the minor (mesiodistal) dimension \( D_{\text{min}} \) of the endodontic access cavity. The full lines represent fits to the function

\[
T_B = T_0(1 + K_{\text{min}}/D_{\text{min}}) \tag{3}
\]

with the same \( K_{\text{min}} = 2.89 \) for all fits, and the infinite cavity oscillation times \( T_0 \) as depicted in Table 1. Similar dependences were obtained also for \( D_{\text{max}} \) (with \( K_{\text{max}} = 3.69 \)) and \( D_{\text{ave}} \) (with \( K_{\text{ave}} = 3.35 \)).

Figure 4 depicts the obtained dependence of the ratio \( T_B/T_0 \) on \( D_{\text{min}} \) (Fig. 4a), \( D_{\text{max}} \) (Fig. 4b), and \( D_{\text{ave}} \) (Fig. 4c), with the best fit to Equation (2) obtained using \( K_{\text{min}} = 2.89, K_{\text{max}} = 3.69, \) and \( K_{\text{ave}} = 3.35 \).

Table 2 shows optimal separation times \( T_{\text{opt}} \) for mesiodistal cavity dimensions \( D_{\text{min}} \) in the range from 1 mm to 5 mm and for laser pulse energies of 10 mJ and 20 mJ. The average values are calculated using Equation (3) and \( K = 2.89 \) and the confidence interval (±50 μs) was estimated from measurements presented in Figure 3.

**DISCUSSION**

The dimensions of endodontic access cavities vary significantly depending on the tooth type and size, dental tissue lost by decay and also on the endodontist’s skill and preference when preparing it [7,40]. LAI bubble generation takes place in the coronal access cavity and accordingly its dimensions effectively conditions the irrigant laser activation. Accordingly, when not using the AutoSWEEPS modality, the X-SWEEPS pulse temporal separation \( T_p \) would at least in principle have to be individually adjusted to the characteristics of each particular access cavity.

In a recent study of bubble dynamics in liquid-filled cylindrical tubes [38], it was shown that the bubble oscillation time \( T_B \) in a long tube can be predicted using a relatively simple relation between \( T_B \) and the tube’s diameter \( D_{\text{cavity}} \) (see Equation 1). This enables predicting the optimal X-SWEEPS separation time in a cylindrically shaped cavity from the known diameter of the tube.

**TABLE 1. Infinite Cavity Oscillation Times \( T_0 \) for Different FTs (Flat Sweeps400 and Radial Sweeps400), Laser Pulse Energies \( E_L \) (in mJ) and Insertion Depths \( h \) (in mm), as Obtained From Fitting the Experimental Data (Fig. 3) to Equation (3)**

| \( E_L \) (mJ) | \( h \) (mm) | \( T_0\) (μs) | \( T_0\) (μs) |
|---------------|-------------|---------------|---------------|
| 10            | 4           | 222 ± 10      | 239 ± 10      |
| 20            | 4           | 270 ± 10      | 290 ± 10      |
| 10            | 2           | 166 ± 10      | 170 ± 10*     |
| 20            | 2           | 214 ± 10      | 220 ± 10*     |

Exceptions are oscillation times marked with an * that were obtained from the measured ratios of bubble oscillation times for flat and radial tips inserted to \( h = 2 \) mm in a simulated endodontic access cavity as used in [35].
influence of the smaller dimension on the bubble dynamics.

The results of this study suggest a further potential improvement of the SWEEPS technique. Endodontic Er:YAG laser devices could be configured to enable the practitioner to define the optimal SWEEPS separation time by simply selecting the characteristic dimension $D_i$ of the particular access cavity. As an example, Table 2 shows the optimal separation times $T_{opt}$ for typical mesiodistal cavity dimensions $D_{min}$ and typical laser pulse energies as calculated using Equation (3) and $K = 2.89$.

A limitation of this study is that the relation between access cavity dimension and bubble oscillation time presented with Equation (3) is validated only within a limited interval of cavity dimensions, from 1 to 6 mm, that however match the in vivo clinical conditions. Especially in a case of significantly smaller cavity dimension the bubble dynamics will deviate from the model assumption as it is described in [24]. A similar deviation is also expected in case the fiber tip is not positioned in the center of the cavity. As can be seen from the results (Fig. 3 and Table 1) the oscillation time also depends on the insertion depth of the fiber tip. This can be accurately controlled in the laboratory environment but more difficult to achieve under in vivo conditions where the fiber tip is manually positioned on a visual basis. Due to the above mentioned limitations, the relation between $T_B$ and $D_i$ is only approximate, and the practitioner would potentially be only estimating the cavity size. However, an improved “Auto X-SWEEPS” modality could also be employed. This improved “Auto X-SWEEPS” modality would consist of the temporal separation between the pair of laser pulses being continuously swept back and forth between $T_{opt} - \Delta T_p$ and $T_{opt} + \Delta T_p$, where $\Delta T_p = 50\,\mu s$ takes into account the observed spread of the actual bubble oscillation times around the predicted optimal separation times based on Equation (3) (See Fig. 4).

The possibility to significantly enhance the effective flushing action of SWEEPS [34], and to increase the pressure generation along the root canal [35,36], without increasing the risk of apical extrusion needs to be explored to assess the safety of “X-SWEEPS” modality. Studies in artificial models with apical constriction of ISO40 [37] and ISO45 [35] and lateral canal opening of ISO35 [35] indicate that the new SWEEPS method does not increase the risk of apical extrusion as compared with the single pulse LAI or standard syringe irrigation. Therefore, when all the parameters are correctly set, the possibility to maintain the irrigation efficacy while decreasing the energy to 15 mJ or 10 mJ [20], promises to offer a safe in vivo procedure also for larger apical opening.

### TABLE 2. Optimal SWEEPS Pulse Separation Times ($T_{opt}$) for Typical Mesiodistal Cavity Dimension ($D_{min}$) at FT Insertion Depth of 4 mm

| FT geometry       | $E_L$ (mJ) | 1 mm       | 2 mm       | 3 mm       | 4 mm       | 5 mm       |
|-------------------|------------|------------|------------|------------|------------|------------|
| Flat Sweeps 400   | 10         | 864 ± 50 $\mu s$ | 543 ± 50 $\mu s$ | 436 ± 50 $\mu s$ | 382 ± 50 $\mu s$ | 350 ± 50 $\mu s$ |
|                   | 20         | 1050 ± 50 $\mu s$  | 660 ± 50 $\mu s$  | 530 ± 50 $\mu s$  | 465 ± 50 $\mu s$  | 426 ± 50 $\mu s$  |
| Radial Sweeps 400 | 10         | 930 ± 50 $\mu s$  | 584 ± 50 $\mu s$  | 469 ± 50 $\mu s$  | 412 ± 50 $\mu s$  | 377 ± 50 $\mu s$  |
|                   | 20         | 1128 ± 50 $\mu s$ | 709 ± 50 $\mu s$  | 569 ± 50 $\mu s$  | 500 ± 50 $\mu s$  | 458 ± 50 $\mu s$  |
CONCLUSIONS

In spite of the generically different dimensions and shapes of endodontic access cavities, the optimal pulse separation time \( T_{\text{opt}} \) between the two Er:YAG laser pulses of the X-SWEEP® modality, emitted at a specific pulse energy and with a specific fiber-tip diameter and shape, can be relatively well predetermined \( (R^2 = 0.73) \) and set for standardized volumes of different access cavities with longer separation times required for smaller cavity dimensions. This finding enables a relatively simple method for determining optimal conditions for shockwave generation and enhanced photographic streaming in differently shaped and sized root canals, leading to improved treatment efficacy and safety of root canal irrigation.

ACKNOWLEDGMENTS

This research was supported by the Ministry of Education, Science and Sport, Slovenia, under grants L2-1833, L3-7658, P2-0392, and Fotona d.o.o.

REFERENCES

1. Stojicic S, Zivkovic S, Qian W, Zhang H, Haapasalo M. Tissue dissolution by sodium hypochlorite: Effect of concentration, temperature, agitation, and surfactant. J Endod 2019;45(1):68–69. https://doi.org/10.1016/j.joen.2018.10.017
2. Zandi H, Rodrigues RC, Kristoffersen AK, et al. Antibacterial effectiveness of 2 root canal irrigants in root-filled teeth with infection: A randomized clinical trial. J Endod 2016;42(9):1307–1313. https://doi.org/10.1016/j.joen.2016.06.006
3. Gazzaneo I, Vieira GCS, Pérez AR, et al. Root canal disinfection by single- and multiple-instrument systems: Effects of sodium hypochlorite volume, concentration, and retention time. J Endod 2019;45(6):736–741. https://doi.org/10.1016/j.joen.2019.02.017
4. Hülsmann M, Peters OA, Dummer PMH. Mechanical preparation of root canals: Shaping goals, techniques and means. Endod Top 2005;10(1):30–76. https://doi.org/10.1111/j.1601-1546.2005.00152.x
5. Peters OA. Current challenges and concepts in the preparation of root canal systems: A review. Journal of Endodontics Aug 2004;30(8):559–567.
6. Peters OA, Schönengerber K, Laib A. Effects of four Ni-Ti preparation techniques on root canal geometry assessed by micro computed tomography. Int Endod J 2001;34(3):221–230. https://doi.org/10.1046/j.1365-2958.2001.00373.x
7. Castellucci A, West JD. Chapter 11 Access Cavity and Endodontic Anatomy. In: Endodontics. vol. 1. Firenze II Tridente: Edizioni Martina, pp. 244–326.
8. Vertucci FJ. Root canal anatomy of the human permanent teeth. Oral Surg Oral Med Oral Pathol 1984;58(5):589–599. https://doi.org/10.1016/0030-4220(84)90085-9
9. Walters MJ, Baumgartner JC, Marshall JG. Effect of irrigation with rotary instrumentation. J Endod 2002;28(12):837–839. https://doi.org/10.1016/S0368-119X(02)01001-1
10. Haapasalo M, Shen Y, Qian W, Gao Y. Irrigation in endodontics. Dent Clin North Am 2010;54(2):291–312. https://doi.org/10.1016/j.cden.2009.12.001
11. Susin L, Yoon JC, Liu Y, et al. Canal and isthmus debridement efficacies of two irrigant agitation techniques in a closed system. Int Endod J 2010;43(12):1077–1090. https://doi.org/10.1111/j.1365-2950.2010.04778.x
12. Bryce G, MacBeth N, Gulabivala K, Ng Y-L. The efficacy of supplementary sonic irrigation using the EndoActivator® system determined by removal of a collagen film from an ex vivo model. Int Endod J 2018;51(4):489–497. https://doi.org/10.1111/iej.12870
13. Chan R, Versiani MA, Friedman S, et al. Efficacy of 3 supplementary irrigation protocols in the removal of hard tissue debris from the mesial root canal system of mandibular molars. J Endod 2019;45(7):923–929. https://doi.org/10.1016/j.joen.2019.03.013
14. Lee S-J, Wu M-K, Wesselinck PR. The effectiveness of syringe irrigation and ultrasonics to remove debris from simulated irregularities within prepared root canal walls. Int Endod J 2004;37(10):672–678. https://doi.org/10.1111/j.1365-2951.2004.00848.x
15. Rödig T, Sedghi M, Konietzchke F, Lange K, Ziebolz D, Hülsmann M. Efficacy of syringe irrigation, RinsEndo® and passive ultrasonic irrigation in removing debris from irregularities in root canals with different apical sizes. Int Endod J 2010;43(7):581–589. https://doi.org/10.1111/j.1365-2951.2010.01721.x
16. De Moor RJG, Blanken J, Meire M, Verdaasdonk R. Laser induced explosive vapor and cavitation resulting in effective irrigation of the root canal. Part 2: Evaluation of the efficacy. Lasers Surg Med 2009;41(7):520–523. https://doi.org/10.1002/lsm.20797
17. Kurzmann C, Meire MA, Lettner S, Farmakis ETR, Moritz A, De Moor RJG. The efficacy of ultrasonic and PIPS (photoinduced acoustic streaming) irrigation to remove artificially placed dentine debris plugs out of an artificial and natural root model. Lasers Med Sci 2020;35(3):719–728. https://doi.org/10.1007/s10103-019-02912-3
18. de Groot SD, Verhaagen B, Versluis M, Wu M-K, Wesselinck PR, van der Sluis LWM. Laser-activated irrigation within root canals: Cleaning efficacy and flow visualization. Int Endod J 2009;42(12):1077–1083. https://doi.org/10.1111/j.1365-2951.2009.01634.x
19. DeVito E, Peters OA, Olivi G. Effectiveness of the erbium:YAG laser and new design radial and striped tips in removing the smear layer after root canal instrumentation. Lasers Med Sci 2012;27(2):273–280. https://doi.org/10.1007/s10103-010-0858-x
20. Golob BS, Olivi G, Vrabc M, El Feghali R, Parker S, Benedicti S. Efficacy of photon-induced photoacoustic streaming in the reduction of Enterococcus faecalis within the root canal: Different settings and different sodium hypochlorite concentrations. J Endod 2017;43(10):1730–1735. https://doi.org/10.1016/j.joen.2017.05.019
21. Awan D, Kustarci A. Efficacy of photon-initiated photoacoustic streaming on apically extruded debris with different preparation systems in curved canals. Int Endod J 2018;51(Suppl 1):e65–e72. https://doi.org/10.1111/iej.12816
22. Ozbay E, Erdemir A. Effect of several laser systems on removal of smear layer with a variety of irrigation solutions. Microsc Res Tech 2018;81(10):1214–1222. https://doi.org/10.1002/jemt.23122
23. De Meyer S, Meire MA, Coenye T, De Moor RJG. Effect of laser-activated irrigation on biofilms in artificial root canals. Int Endod J 2017;50(5):472–479. https://doi.org/10.1111/iej.12643
24. Lučan N, Jezeršek M. Amplification of pressure waves in laser-assisted endodontics with synchronized delivery of Er:YAG laser pulses. Lasers Med Sci 2018;33(4):823–833. https://doi.org/10.1007/s10103-017-2435-5
25. Yokazaki R, Goya C, Yu DG, Kimura Y, Koutchki Matsumoto K. Effects of erbium,chromium:YSGG laser irradiation on root canal walls: A scanning electron microscopic and thermographic study. J Endod 2001;27(1):9–12. https://doi.org/10.1016/S0022-2396(00)00093-8
26. Gregorić P, Jezeršek M, Možina J. Optodynamic energy-conversion efficiency during an Er:YAG-laser-pulse delivery into a liquid through different fiber-tip geometries. J Biomed Opt 2017;22(7):075006. https://doi.org/10.1117/1.JBO.21.7.075006
27. Lukac N, Zadravec M, Greco F, Lukac M, Jezeršek M. Wavelength dependence of photon-induced photoacoustic streaming technique for root canal irrigation. J Biomed Opt 2016;21(7):75007. https://doi.org/10.1117/1.JBO.21.7.075007
28. Matsumoto H, Yoshimine Y, Akamine A. Visualization of irrigant flow and cavitation induced by Er:YAG laser within a root canal model. J Endod 2011;37(6):839–843. https://doi.org/10.1016/j.joen.2011.02.035

LUKAČ ET AL. 1003
29. Swimberghe RCD, De Clercq A, De Moor RJG, Meire MA. Efficacy of sonically, ultrasonically and laser-activated irrigation in removing a biofilm-mimicking hydrogel from an isthmus model. Int Endod J 2019;52(4):515–523. https://doi.org/10.1111/iej.13024

30. Lukač N, Gregorčič P, Jezeršek M. Optodynamic phenomena during laser-activated irrigation within root canals. Int J Thermophys 2016;37(7):66. https://doi.org/10.1007/s10765-016-2071-z

31. Koch JD, Jaramillo DE, DiVito E, Peters OA. Irrigant flow during photon-induced photoacoustic streaming (PIPS) using particle image velocimetry (PIV). Clin Oral Invest 2016;20(2):381–386. https://doi.org/10.1007/s00784-015-1562-9

32. Lukac N, Muc BT, Jezersek M, Lukac M. Photoacoustic endodontics using the novel SWEEPS Er:YAG laser modality. J Laser Health Acad 2017;1:1–7.

33. Gregorčič P, Lukač N, Možina J, Jezeršek M. Synchronized delivery of Er:YAG-laser pulses into water studied by a laser beam transmission probe for enhanced endodontic treatment. Appl Phys A: Mater Sci Process 2016;122(4):459. https://doi.org/10.1007/s00339-016-9970-5

34. Jezeršek M, Lukač N, Lukač M. Measurement of simulated debris removal rates in an artificial root canal to optimize laser-activated irrigation parameters. Lasers Surg Med. https://doi.org/10.1002/lsm.23297

35. Jezeršek M, Lukač N, Lukač M, Tenyi A, Olivi G, Fidler A. Measurement of pressures generated in root canal during Er:YAG laser-activated irrigation. Photobiomodul Photomed Laser Surg 2020;58(10):625–631. https://doi.org/10.1089/photob.2019.4776

36. Galler KM, Grubmüller V, Schlichting R, et al. Penetration depth of irrigants into root dentine after sonic, ultrasonic and photoacoustic activation. Int Endod J 2019;52(8):1210–1217. https://doi.org/10.1111/iej.13108

37. Jezeršek M, Jereb T, Lukač N, Tenyi A, Lukač M, Fidler A. Evaluation of apical extrusion during novel Er:YAG laser-activated irrigation modality. Photobiomodul Photomed Laser Surg 2019;57(9):544–550. https://doi.org/10.1089/photob.2018.4608

38. Lukač M, Lukač N, Jezeršek M. Characteristics of bubble oscillations during laser-activated irrigation of root canals and method of improvement. Lasers Surg Med 2020;52(9):907–915. https://doi.org/10.1002/lsm.23226

39. Yang Q, Liu MW, Zhu LX, Peng B. Micro-CT study on the removal of accumulated hard-tissue debris from the root canal system of mandibular molars when using a novel laser-activated irrigation approach. Int Endod J 2020;53(4):529–538. https://doi.org/10.1111/iej.13250

40. Alovisi M, Pasqualini D, Musso E, et al. Influence of contracted endodontic access on root canal geometry: An in vitro study. J Endod 2018;44(4):614–620. https://doi.org/10.1016/j.joen.2017.11.010

41. Krapež J, Fidler A. Location and dimensions of access cavity in permanent incisors, canines, and premolars. J Conserv Dent 2013;16(5):404–407. https://doi.org/10.4103/0972-0707.117491

42. Ingle JJ, Bakland LK. Endodontics. 4th edition. Baltimore: Williams & Wilkins; 1994.