ISSN 1855-9913

Journal of the Laser and Health Academy
Vol. 2019, No.1; www.laserandhealth.com

SSP/SWEEPS Endodontics with the SkyPulse Er:YAG Dental Laser

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ABSTRACT

The goal of endodontic treatment is to obtain effective cleaning and decontamination of the smear layer, bacteria and their byproducts within the root canal system. Clinically, traditional endodontic techniques use mechanical instruments as well as ultrasonic and chemical irrigation in an attempt to shape, clean and completely decontaminate the endodontic system, but still fall short of successfully removing all of the infective microorganisms and debris.

Laser-activated irrigation is a powerful endodontic treatment for removal of the smear layer, bacteria, and debris from the root canal. Numerous studies have shown that photon-induced photoacoustic streaming using SSP-activated Er:YAG laser irrigation has significantly higher efficacy compared to traditional methods such as syringe or ultrasonic needle irrigation. This is attributed to extremely rapid opto-dynamic phenomena during SSP-assisted activation. In this study, root canal pressure measurements were carried out in order to further optimize the fiber tip geometry for SSP endodontics.

Recently, a newer SWEEPS® Er:YAG laser modality was introduced with the goal to enhance the disinfecting and activating efficacy of SSP laser-assisted endodontic procedures by enabling primary and secondary shock waves to be generated throughout the complex root canal system. As is shown in this paper, the SWEEPS modality significantly enhances the efficacy of the removal of debris and medicaments from the root canal system.

The complementary combination of the SSP and SWEEPS® technologies in most recent Er:YAG dental laser devices thus represents a unique solution for modern endodontics.

Key words: Er:YAG, SSP, SWEEPS, laser-assisted irrigation, laser endodontics, photon-induced photoacoustic streaming, shock wave enhanced emission photoacoustic streaming.

Article: J. LA&HA, Vol. 2019, No.1; pp. 1-10.
Received: June 28, 2019; August 29, 2019.

I. INTRODUCTION

The goal of endodontic therapy is to eliminate pathogenic substances from the root canal system [1]. However, standard mechanical instrumentation leaves a significant portion of the complex root canal system un-instrumented [2]. Additionally, the mechanical instrumentation itself creates a smear layer and an accumulation of debris that need to be removed as well [3]. For this reason, an irrigation phase of the therapy is required in order to eliminate the potential pathogens, and to remove the debris resulting from the instrumentation phase of the procedure [4,5].

Different methods and technologies have been introduced with the goal to improve the efficacy of the standard syringe root canal irrigation procedure [6-13]. One of the most recent techniques involves SSP/SWEEPS® laser-assisted irrigation (LAI) using a special type of the Er:YAG (erbium-doped yttrium aluminum garnet) laser with extremely short laser pulses, generating photon-induced photoacoustic streaming of the irrigant throughout the complex three-dimensional root canal system [14-19] (Fig.1).

Fig. 1: Laser-assisted irrigation technique using SSP/SWEEPS Er:YAG laser technology. The laser fiber tip is placed in the coronal portion of the pulpal chamber, and left stationary, allowing the photoacoustic waves to spread into the openings of each canal. The placement of the tip in only the coronal portion of the treated tooth allows for a more minimally enlarged canal preparation, and without thermal damage as is seen with techniques requiring placement into the canal system.

The photon-induced photoacoustic streaming is achieved through the high absorption of the SSP (Super Short Pulse; 50 μs) Er:YAG laser pulse in the irrigant [14], which initiates the rapid formation of a vapor bubble at the fiber tip (FT) while it is immersed in the irrigant [20, 21]. Due to the very high absorption coefficient of the Er:YAG laser wavelength (λ = 2940 nm) in irrigants, all of the laser pulse light is absorbed within the approximately 1 μm-thick fluid layer. Thus, the fluid is locally and instantly heated over the boiling point and a vapor bubble starts to form at the FT's end.

After the explosive boiling, the vapor bubble starts to expand (See Fig. 2). When it reaches its maximum volume it is nearly empty and it starts to collapse due to the pressure of the surrounding liquid [22]. This phenomena induces turbulent fluid movement within the whole root canal volume, significantly improving the efficacy of chemo-mechanical debridement [14, 19].

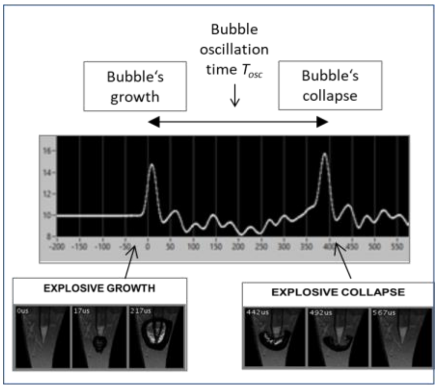

Fig. 2: SSP laser endodontics is performed with single Er:YAG laser pulses in the SSP (Super Short Pulse) emission mode. During SSP laser-assisted irrigation the initial growth and collapse of the vapor bubble (bubble images below, [21]) are so explosive that they can be detected with a microphone (acoustic signal above). The time duration between the bubble's start-up and the first collapse is defined as the bubble's oscillation time, T_{osc} .

Extremely short (SSP) laser pulses are required in order to avoid the effects of thermal diffusion during the bubble life-time [23]. Namely, the opto-dynamic energy-conversion efficiency is reduced by the residual heat that remains deposited in the thin fluid layer extending from the vapor liquid interface deeper into the liquid. For super-short laser pulses, the effects of thermal diffusion during bubble formation are minimal.

The ultimate goal of SSP/SWEEPS is to significantly enhance several irrigation mechanisms [14]: i) 3-D streaming of the irrigant throughout the complex root canal system; ii) Increased penetration of the irrigant deeper into the dentinal tubules; iii) Removal of debris and the smear layer from the root canal system; iv) More effective chemical activation of NaOCl; v) Direct (non-chemical) removal of biofilm; and vi) Direct (non-chemical) disinfection.

The clinical efficacy and safety of SSP laser-assisted irrigation has been extensively investigated [13-19]. However, research indicates that further improvements can be achieved by tailoring the Er:YAG laser emission characteristics to the specific requirements of the above irrigation mechanism [21].

This has led to the development of SSP/SWEEPS® endodontics, where the extremely effective single-pulse SSP irrigation is complemented with an additional, dual-pulse SWEEPS® (Shock Wave Enhanced Emission Photoacoustic Streaming) technique [21, 24-27]. The SWEEPS® modality is based on the finding that, as opposed to large liquid reservoirs, shock waves, i.e., waves travelling faster than sound, are not observed in spatially confined reservoirs such as root canals [24]. This is because in narrow canals cavitation dynamics are significantly slowed down by the friction on the canal walls and by the limited space available for the quick displacement of the liquid during the bubble's expansion and contraction. The SWEEPS modality consists of delivering a subsequent laser pulse into the liquid at an optimal time T_{opt} when the initial bubble is in the final phase of its collapse, i.e. just before $t = T_{osc}$ (see Fig. 3 ii). The growth of the second bubble exerts pressure on the collapsing initial bubble, accelerating its collapse and the collapse of secondary bubbles, resulting in the emission of primary and also secondary shock waves.

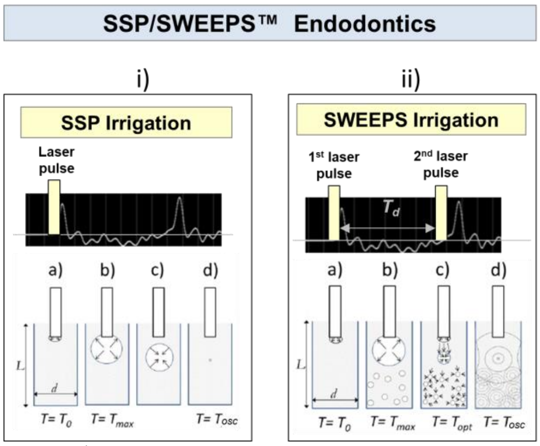

Fig. 3: SSP/SWEEPS endodontics with (i) single-pulse SSP and (ii) dual-pulse SWEEPS laser-assisted irrigation. In the SWEEPS dual-pulse sequence, the initial laser pulse is followed by a subsequent laser pulse delivered at an optimal time – when the initial bubble generated by the first pulse is in the final phase of collapse (Fig. iic). The additional pressure caused by the growth of the second bubble accelerates the collapse of the first bubble (Fig. iic), resulting in the emission of primary and secondary shock waves (Fig. iid).

The clinical efficacy and safety of laser-assisted SSP irrigation has been extensively investigated [13-19]. In this paper, we report on the enhanced cleaning efficacy of the SWEEPS modality, improving even further the efficacy of the laser-assisted removal of debris and medicaments from the complex root canal system.

Additionally, we report on measurements of irrigant pressures at different depths within a model root canal for different fiber tip geometries. Since irrigant pressures are related to the efficacy of 3D streaming and the ability of different irrigation solutions to deeply penetrate the root canal walls [28-30], the pressure measurements were then used to optimize the fiber tip geometry for SSP/SWEEPS® endodontics.

II. MATERIALS AND METHODS

The Er:YAG laser (λ = 2940 nm) used in this study was the SkyPulse (Fotona d.o.o., Ljubljana, Slovenia), equipped with the H14 handpiece, optically coupled with interchangeable fiber tips (See Fig. 4). The handpiece air/water spray was turned off during all experiments. The following fiber tips were used in the study:

a) **Flat tips:** cylindrical flat-ended fiber tips with diameters of 300 µm (Flat Sweeps300), 400 µm (Flat Sweeps400) 500 µm (Flat Varian500) and 600 µm (Flat Varian600);*
b) **Radial tips:** cylindrical radially-ended (tapered) tips with diameters of 400 µm (Radial Sweeps400) and 600 µm (Radial Sweeps600). Note that the Radial Sweeps600 tip is geometrically equivalent to the standard 600 µm "PIPS" fiber tip [14].**
c) **Conical tips:** conical flat-ended tips with diameters of 400 µm (Conical Sapphire 400) and 600 µm (Conical Sapphire 600).

The SkyPulse laser system was operated in the single-pulse SSP emission mode and in the dual-pulse SWEEPS emission mode. Since the proper timing of the SWEEPS pulse pair depends on the cavitation bubble's oscillation time, which depends on the geometry of the access chamber [21, 26], the SkyPulse's SWEEPS modality consists of automatic repetitive sweeping of the temporal separation (T_d) between the SWEEPS pulse pair back and forth within an optimal range of temporal separations in order to ensure effective irrigation regardless of the tooth type and chamber size preparation.

Fig. 4: The SkyPulse Er:YAG laser system used in the study. The laser system is equipped with the two latest laser-assisted irrigation modalities: SSP and SWEEPS, thus enabling a complete SSP/SWEEPS endodontic treatment.

It is the accelerated collapse of the first bubble in the SWEEPS pulse pair that results in the enhanced shock wave emission and improved irrigation, while the role of the second bubble is mainly to amplify the effect of the first bubble. Also, during an endodontic procedure the endodontist has to be careful to not exceed the threshold for dentinal ablation, which depends on the energy of the individual laser pulses. Therefore, the relevant laser energy for the SWEEPS-type modality is the single-pulse energy E_L of the pulses within the "SWEEPS" pulse pair.

a) Measurement of root canal pressures

Figure 5 shows the experimental system for the measurement of pressures at different depths within a model root canal. A simulated tooth model with the entrance diameter of the conically shaped access cavity of 3 mm was submerged 4 mm deep under the water level of a large water-filled reservoir. This provided a stable fluid pressure within the root canal in the absence of LAI, and enabled constant replenishment of irrigant.

The laser fiber tip's end was positioned 2.5 mm deep into the access chamber. The tooth model had five openings ($O_1 \ldots O_5$; see Fig. 5) located at different depths of the root canal, consisting of five tubular constrictions. The lateral constrictions (i=2…5) had approximate diameters d_i = 0.45 mm and lengths l_i =3.5 mm, while the vertical (apical) constriction's approximate dimensions were d_1 = 0.2 mm and l_1=1 mm. The constrictions were connected to tubes with a larger internal diameter of 1.6 mm. The tubes ended with an approximately vertical section extending approximately 10 cm above the water level of the large reservoir.

* Previous manufacturer's codes for cylindrical flat 300, 400, 500 and 600 µm fiber tips were Preciso300, Varian400, Varian 500 and Varian600, correspondingly.

** Previous manufacturer's codes for tapered cylindrical 400 and 600 µm fiber tips were XPulse400, and XPulse600, correspondingly

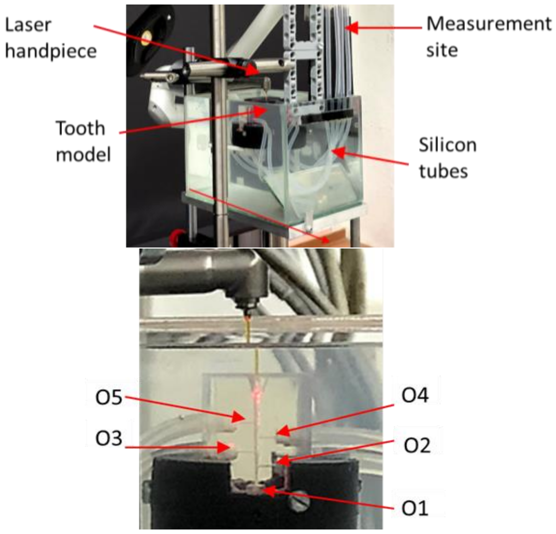

Fig. 5: Experimental system for measuring pressures (above) at different locations O1-O5 within the root canal model (below).

The measuring principle was based on measuring the heights of the water columns inside the five tubes during LAI. In the absence of laser delivery, the water levels within the tubes were aligned with the large reservoir's water surface level at h_i (i = 1-5) ≡ 0, as required for a connecting vessel set-up. A digital camera was used for measuring the water level heights simultaneously for all five water columns. A custom computer program using graphical programming software was developed for real-time detection of water levels from the acquired video data. The program detects brightness decreases within each tube, calculates the height difference between the water levels within the tubes and the large reservoir, and stores the measured values, h_i.

During simulated irrigation conditions, laser pulses were delivered through the FT into the access cavity at a constant repetition rate. When laser radiation was turned on, the fluid columns h_i started to rise as a result of the increased pressure within the root canal, until they reached their individual equilibrium heights, h_{oi}. The equilibrium was reached when the average upward volumetric fluid flow rate Q_{ui} (in mm^3/s), became equal to the constant downwards fluid flow rate Q_{di} caused by the pressure difference in the connecting vessel due to the increased height of the water columns relative to the reservoir's water surface. Because of this pressure difference, the height of the water columns started to decrease immediately after laser radiation was turned off, at the height-dependent decrease rate of v_i (h_i) = dh_i/dt (in mm/s). Since at the equilibrium the upward average fluid flow during LAI was equal to the downward flow at the equilibrium height, h_{oi}., this allowed the determination of the upward flow and subsequently the pressures as generated during LAI.

The pressure differences (P_i) between the two ends of the narrow constrictions (Oi) were then calculated using the Hagen–Poiseuille equation [31, 32], defining the pressure difference in an incompressible and Newtonian fluid that is required to result in the upward flow rate Q through the vertical height measurement tubes. The average generated pressures (P_{ave}) for different irrigation protocols were calculated using $P_{ave} = (P_1+P_2+P_3+P_4+P_5)/5$.

The SkyPulse Er:YAG laser was set to emit radiation in the single pulse "SSP" (Super Short Pulse) emission mode. For comparison, measurements with another Er:YAG laser device, LightWalker (Fotona d.o.o., Ljubljana, Slovenia) were also made under the same conditions and using the same handpiece (H14) and fiber tips. Both lasers were operated with the single-pulse energy of E_L = 20 mJ and a repetition rate of f =15 Hz.

b) Measurement of debris removal rate

The root canal model used for measuring the cleaning efficacy is shown in Fig. 6. The experimental set-up consisted of a transparent root canal model, submerged in a glass container filled with distilled water. The root canal model was filled-up with a suspension paste to simulate debris. A biological calcium hydroxide based paste was used in the validation phase of the experiment. In the measurement phase, a gel dentifrice was used, which yielded comparable results to the biological paste but was easier to handle and required less time to empty and re-fill the root canal model between measurements.

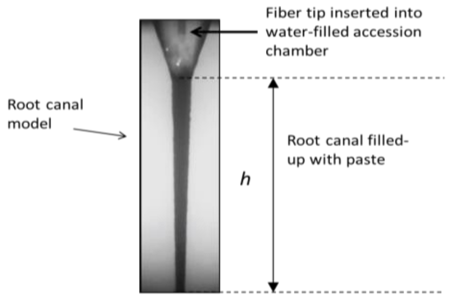

Fig. 6: Experimental root canal model system for measuring debris removal rates. Before each measurement, the root canal was completely filled-up with the suspension paste.

Laser pulses with a single-pulse energy of E_L = 20 mJ were delivered through the Flat Sweeps400 fiber tip positioned inside the root canal model. The images of the root canal during LAI were captured by a video camera and analyzed using custom-developed software. Before each measurement, the root canal was completely filled-up with the paste (Fig. 7 left). The cleaning rate R_c was determined from the measured reduction Δh of the height h of the simulated debris within the root canal model, $R_c = \Delta h / T_{ir}$, with the irrigation time T_{ir} = 180 s. Shorter irrigation times were used for calculation when the root canal became fully cleaned, i.e., emptied of the paste, already before the expiry of 180 s. Each cleaning rate data point represents an average of at least five repeated irrigations.

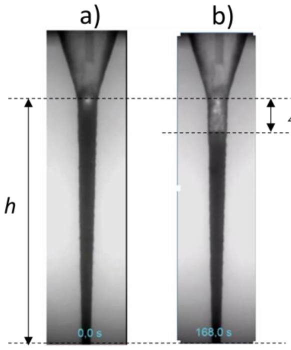

Fig. 7: Image of the filled-up root canal prior to irrigation (a) and image of the partially cleaned root canal following an irrigation sequence (b).

The cleaning rate measurements were made for the single-pulse SSP emission mode and for the automatically swept SWEEPS emission mode.

III. RESULTS

a) Pressure measurements

Figure 8 shows the measured dependence of the generated fluid pressure on the fiber tip type and laser device. For easier comparison, average pressures $P_{ave} = (P_1+P_2+P_3+P_4+P_5)/5$ are shown. Both Er:YAG laser devices, LightWalker (LW) and SkyPulse (SKY) operated in the SSP pulse modality with E_L =20 mJ and f = 15 Hz. Measurements show that the SSP emission modes of the SkyPulse and LightWalker laser devices are substantially equivalent.

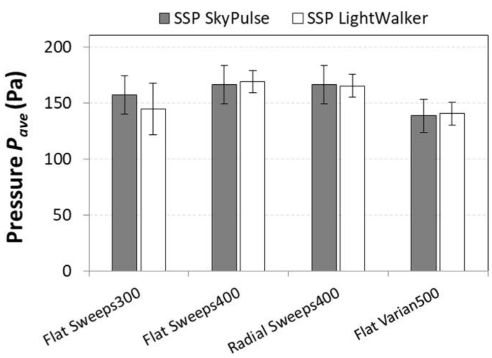

Fig. 8: Average pressure within the root canal for different fiber tip types, and the same single-pulse energy of E_L = 20 mJ in the SSP emission mode of SkyPulse and LightWalker laser systems.

Dependence of average pressures P_{ave} (as measured for both laser devices in SSP mode) on fiber tip type (radial, flat or conical) and diameter is shown in Fig. 9.

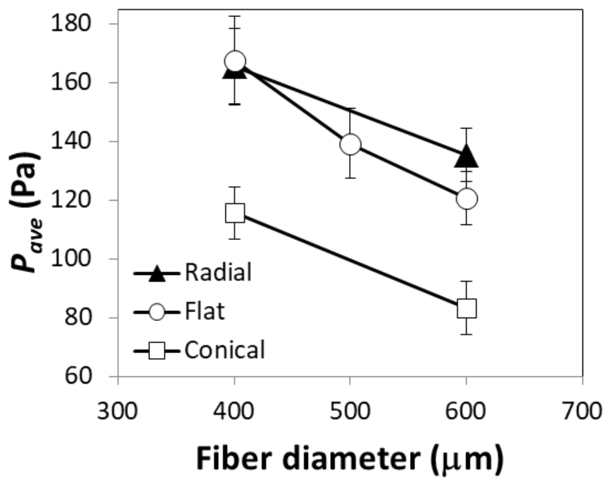

Fig. 9: Dependence of pressure generation efficacy on fiber tip type and diameter.

Detailed pressure distributions within the root canal, as measured with the SkyPulse in SSP mode, are presented in Fig. 10 for different fiber tip types.

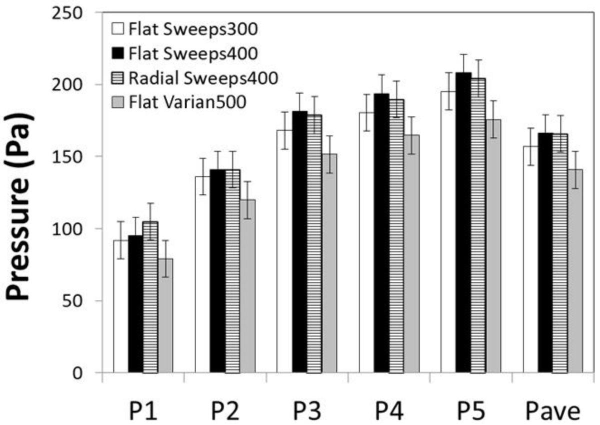

Fig. 10: Measured pressures at different locations within the root canal for different fiber tips. The SSP mode with E_L = 20 mJ at 15 Hz, delivered by a SkyPulse Er:YAG laser device, was used.

The distribution of irrigant pressures within the root canal as shown in Fig. 10 are in agreement with the reported irrigant penetration depths at different root canal areas [29].

IV. CLEANING RATE MEASUREMENTS

The measured debris removal (i.e., cleaning) rates (R_c) for the SkyPulse SSP and SWEEPS emission modes with single-pulse energy E_L = 20 mJ are shown in Fig. 11. The SWEEPS mode was delivered at f = 20 Hz while the SSP emission mode was tested in the range of f = 15-50 Hz, in order to determine whether doubling the single-pulse repetition rate of the SSP mode would yield similar results as the dual-pulse SWEEPS mode.

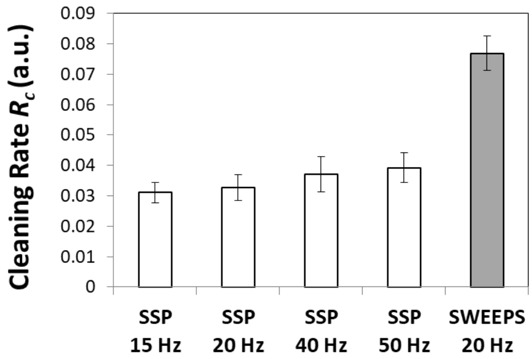

Fig. 11: Debris removal rates R_c for the SSP and SWEEPS emission modes with single-pulse energy E_L = 20 mJ. The SWEEPS mode exhibits a significantly enhanced cleaning rate.

As can be seen from Fig. 11, the debris removal rate of the dual-pulse SWEEPS mode is significantly higher in comparison to the single-pulse SSP mode, regardless of the SSP mode's repetition rate.

V. DISCUSSION

The goal of endodontic treatment is to obtain effective cleaning and decontamination of the smear layer, bacteria and their byproducts within the root canal system. Clinically, traditional endodontic techniques use mechanical instruments as well as ultrasonic and chemical irrigation in an attempt to shape, clean and completely decontaminate the endodontic system, but still fall short of successfully removing all of the infective microorganisms and debris.

The latest SSP/SWEEPS® technology greatly simplifies root canal therapy while successfully addressing all of the ultimate goals of endodontic irrigation [14]: 3-D streaming of the irrigant throughout the complex root canal system, increased penetration of the irrigant deeper into the dentinal tubules, removal of debris and smear layer from the root canal system, more effective chemical activation of NaOCl, direct (non-chemical) removal of biofilm, and direct (non-chemical) disinfection.

a) 3-D irrigant streaming

The high absorption of temporally super-short Er:YAG laser light leads to explosive boiling of the irrigant that generates oscillating vapor bubbles (See Fig. 12), causing the mixing of liquid also at distant regions of the complex root canal anatomy.

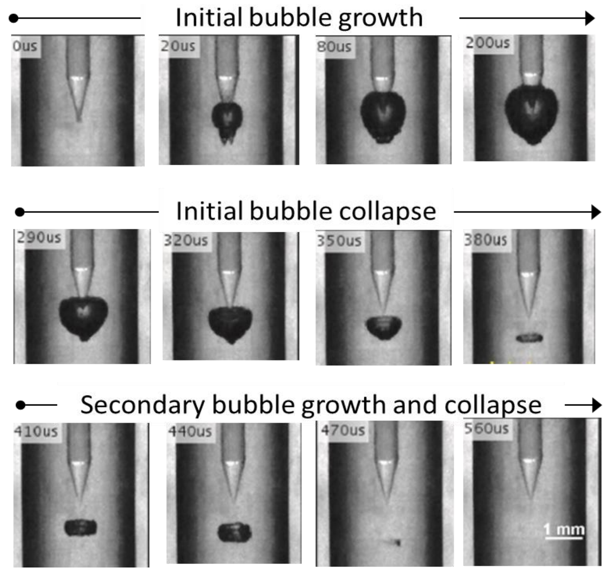

Fig. 12: A typical sequence of images of a bubble captured at different times after the beginning of an SSP laser pulse. The laser-energy deposition causes water to superheat, and its explosive boiling induces a vapor bubble. After the laser-induced boiling, the high pressure of the vapor leads to the rapid expansion of the bubble's volume, observed in images from 0 to 200 µs. During the expansion, the bubble passes over the equilibrium state. Thus, at its maximum volume, the internal pressure is lower than the pressure in the surrounding liquid. This difference in pressures forces the bubble to collapse (e.g., see images from 290 to 380 µs in Fig. 2). The collapse, in turn, can initiate secondary oscillations of the bubble, as visible from 410 to 560 µs [21].

Observations of debris particles show that liquid vorticity effects continue long after the bubble oscillation has ended, significantly contributing to the SSP/SWEEPS irrigation efficacy (See Fig. 13) [20, 21].

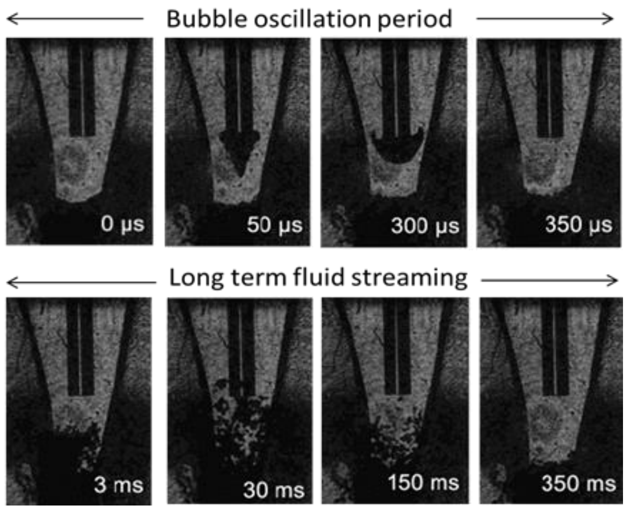

Fig. 13: The series of images shows water vorticity after a SSP laser-induced cavitation bubble using simulated debris particles. Significant water flow can be observed 2 ms after the beginning of the laser pulse, which is long after the collapse of the cavitation bubble (T_{osc} ≈ 300 µs). The particles settle to the ground in approximately 200 ms to 300 ms [21].

Using the SSP/SWEEPS technique, it is now possible to effectively debride and disinfect isthmi, cul-de-sacs, lateral canals, and apical ramifications. In one of the reports [12, 21], SSP irrigation efficacy was studied using a root canal model with a lateral canal as shown in Fig. 14. The fluid motion achieved within the lateral canal during SSP activation was at a speed of 1.5 mm/s, which is sufficient for the irrigation of any lateral canal.

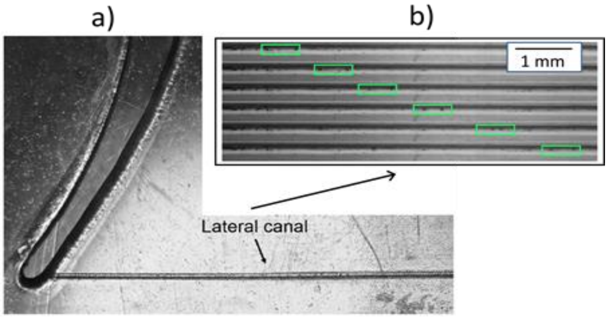

Fig. 14: a) Root canal model with lateral canal used in the experiment. The lateral canal was ≈13.5 mm long and had a diameter of 70-160 μm; b) Observed motion of gas bubbles within the lateral canal during SSP irrigation. [21].

b) Penetration of irrigants into dentinal tubules

Traditional irrigation during root canal treatment with a syringe and needle is associated with only limited penetration beyond the main canal into dentinal tubules [35]. The limitation is particularly pronounced in the apical area.

The SSP/SWEEPS activation considerably increases the efficacy of the irrigants in the apical area, as demonstrated also by the pressure measurements in this study. The pressures measurements during SSP activation show the pressures in the apical region (P_a), represented by the average $P_a = (P_1+P_2)/2$, to be significant, by a factor of only 1.6-times smaller than the average pressure in the coronal region $P_c = (P_4+P_5)/2$ (See Fig. 10). This is in agreement with a study [29], which compared different methods of activation of endodontic irrigants including ultrasonic, sonic and SSP, and determined that SSP activation achieved the greatest penetration depths in the middle and apical sections.

c) Cleaning - removal of debris and smear layer

Using conventional syringe irrigation, it is also difficult to rinse any remaining debris out of the anatomic irregularities before filling the root canal with an inert material.

Shadow photography measurements have revealed important phenomenological differences between ultrasonic needle irrigation and SSP/SWEEPS, with the laser method resulting in much deeper irrigation (see Fig. 15) [20, 21]. This is an important advantage over ultrasonic needle irrigation, where a significant effect occurs only in the close proximity of the instrument [33]. It is for this reason that the ultrasonic needle needs to be inserted down to the apex, which requires larger widening of the root canal, and also introduces the risk of needle breakage. Furthermore, ultrasonic irrigation is problematic in curved and complex root canal geometries as efficiency is reduced by the instrument touching the canal walls [34].

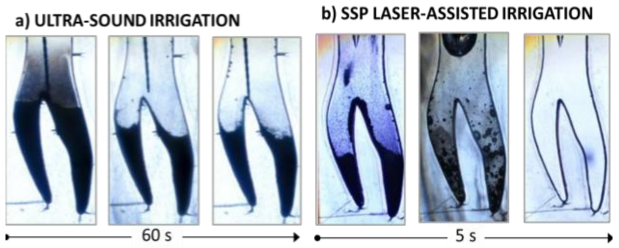

Fig. 15: Comparison between ultrasonic (a) and laser (b) irrigation. Images on the left show the state of the root canal before the treatment, with the ultrasonic file (a) or laser fiber tip (b) inserted. The laser irrigation treatment lasted for 5 s while the ultrasound irrigation effectively ended after 2 s, after which no further irrigation occurred even though the ultrasound device was left on for 60 s. Images in the middle show activity in the root canal during irrigation. The after-treatment photos (images on the right) were taken a minute after the end of each treatment to allow for any debris particles to settle [21].

The present study shows that the latest SWEEPS modality significantly enhances the debris removal efficacy even in comparison to the SSP irrigation (See Fig. 11). As an example, Fig. 16 shows the observed difference in the efficacy of debris removal of the SSP and SWEEPS irrigation.

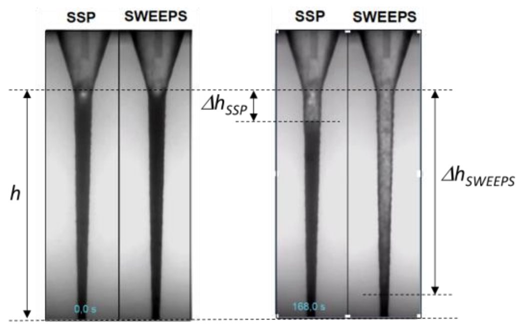

Fig. 16: Images of the filled-up root canal prior to irrigation (left) and images of the partially or fully cleaned root canal following the irrigation sequence (right). An exemplary comparison of the cleaning outcomes following irrigation with SSP and SWEEPS emission mode is shown.

d) Activation, disinfection and biofilm removal

A major mechanism of action of the SSP laser-activated root canal irrigation techniques is believed to be the rapid fluid motion in the canal as a result of expansion and implosion of vapor bubbles, resulting in a more effective delivery of the irrigants throughout the complex root canal system [7, 15]. An additional mechanism which contributes to the efficacy of SSP is the improved removal of the smear layer, microorganisms, and biofilm as a result of the physical action of the turbulent irrigant [7, 15]. In addition, chemical action seems to play a role as well [18, 28]. For example, an increased reaction rate of NaOCl was found to occur upon activation by the pulsed erbium laser [28].

By being able to generate shock waves within narrow root canals, both the physical and chemical actions of SSP can be potentially further enhanced by using the SWEEPS technique.

Figure 17 shows typical shadow-graphic images of shockwaves as observed during the collapse of a single cavitation bubble in an infinite liquid reservoir [21, 24]. Since the shockwave causes a strong disturbance of water's refractive index, it can be visualized as a sharp circular edge on the shadow-graphic images (yellow arrows are pointing to some of them). It should be noted that multiple shockwaves are generated as a consequence of a divided bubble's collapse. This is especially evident when a flat fiber tip is used.

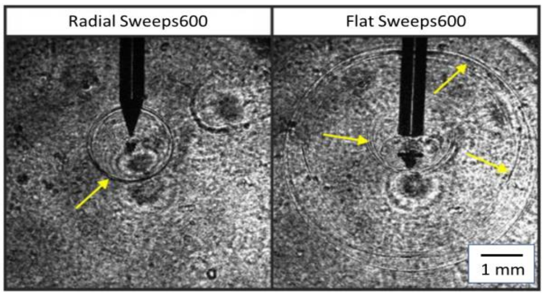

Fig. 17: Typical images of shock waves recorded for a single laser pulse in an infinite liquid reservoir for radial (left) and flat (right) Sweeps600 (cylindrical 600 µm) fiber tips [21].

As opposed to a single bubble collapse in an infinite reservoir, no shock waves were observed during the collapse of a single cavitation bubble in spatially limited closed-ended tooth models [21, 24], in agreement with previous reports [38]. However, when a subsequent laser pulse is emitted during the initial bubble's collapse, the growth of the subsequent bubble exerts pressure on the collapsing initial bubble. This accelerates the collapse of the initial bubble and causes the emission of shock waves even in spatially limited tooth canals. Figure 18 shows shadow-graphic images of shockwaves being emitted during the collapse of an initial cavitation bubble in a narrow model tooth canal. The beginning of a subsequent bubble expansion can be noticed on all images, which indicates that the collapse of the initial bubble was accelerated by a properly delayed subsequent laser pulse. Smaller secondary bubbles are also formed alongside the entire canal since the violent collapse of the initial bubble also initiates the collapses of the secondary bubbles.

The SWEEPS technique shares similarities with extracorporeal shock wave lithotripsy (ESWL), where focused ultrasonic waves are used to break kidney stones into smaller pieces [36, 37].

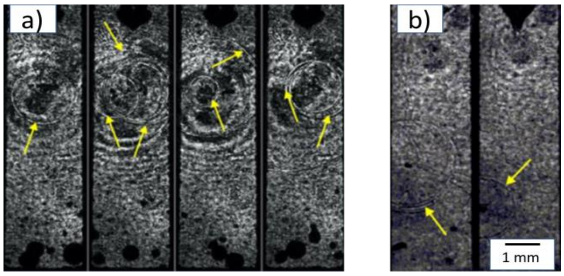

Fig. 18: a) Four examples of detected shock waves in a model tooth canal during SWEEPS activation. The beginning of the formation of the subsequent bubble caused by the second pulse of the SWEEPS pulse pair, can be seen at the bottom of the flat fiber tip; b) Two examples of detected shock waves being emitted by the collapsing secondary bubbles [21].

Under the conditions for SWEEPS shock wave generation, there was also a significant amplification of pressure waves observed [24]. Figure 19 shows the measured dependence of the pressure wave amplitude on the temporal separation T_d of the SWEEPS laser pulse pair [21].

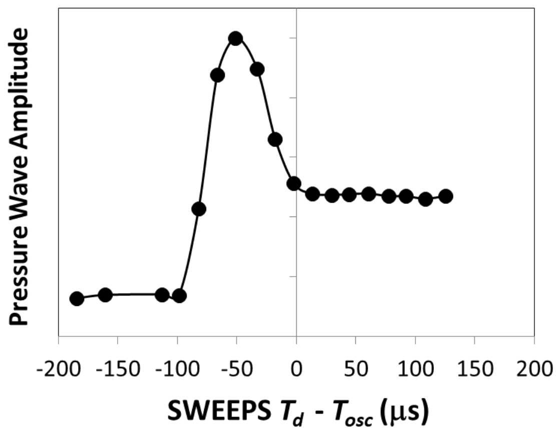

Fig. 19: Pressure wave amplitude as measured below the fiber tip, as a function of the difference between the SWEEPS pulse pair delay T_d and the primary bubble oscillation time T_{osc} [21].

As expected, the conditions for shock wave generation are established when the second laser pulse is emitted just before the collapse of the first bubble. In the presented case, these conditions are reached when the second pulse is emitted ≈ 50 µs before the total collapse of the first bubble.

On the other hand, our measurements show that the debris removal is most effective when the temporal separation between the SWEEPS pulse pair is approximately 50 µs longer than the bubble oscillation time (See Fig. 20).

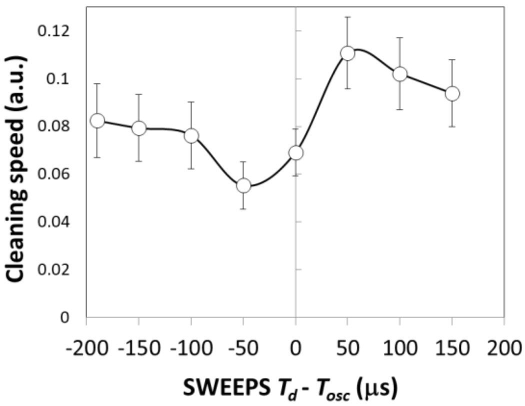

Fig. 20: Measured dependence of the cleaning rate on the temporal separation T_d of the "SWEEPS" pulse pair generated with SkyPulse SSP mode laser pulses with single-pulse energy E_L = 20 mJ.

This indicates that due to the complex photo-acoustic dynamics during dual-pulse irrigation, different activation mechanisms do not have exactly the same "resonant" laser pulse pair separation. In this regard, the auto-sweeping SWEEPS modality has an additional advantage since it covers all "resonances" during the sweeping cycle.

e) Minimal risk of extrusion

It is important to note that the SSP/SWEEPS irrigation does not result in any increase of apical irrigant extrusion. Recently, a study of the apical irrigant extrusion during SSP and SWEEPS laser irrigation was carried out [39], during which irrigation using two standard endodontic irrigation needles (notched open-end and side-vented) was compared with the PIPS and SWEEPS laser irrigation procedures. In the standard irrigation experiment, the irrigation device was a syringe coupled to either a 30-G open-ended or side-vented needle, with flow rates of 1, 2, 5 and 15 mL/min. Both the PIPS and SWEEPS irrigation procedures resulted in a significantly lower apical extrusion compared to the conventional irrigation with endodontic irrigation needles, in agreement with previous reports [40, 41].

f) Optimal fiber tip for SSP/SWEEPS endodontics

Pressure measurement results (See Figs. 8 and 9) show that in general the pressure generation efficacy is higher for smaller fiber tip diameters.

Cylindrical tips exhibited higher efficacy in comparison to conically-shaped fiber tips. This explains why in a recent study [29], which compared SSP activation with a cylindrical radially-ended tip (Radial Sweeps600) and EL = 20 mJ, and SWEEPS activation carried out with the inferior conical tip (Conical Sapphire 600) and also using two-times lower single pulse energy (EL =10 mJ), the irrigant penetration into dentinal tubules was found to be higher for the SSP mode.

The highest efficacy was observed for the following cylindrical tips: Radial Sweeps400 and Flat Sweeps400 tips (Fig. 9), with no significant difference between the two fiber tip types. For the larger fiber tip diameter of 600 µm, the radially-ended fiber tip was slightly more effective than the flat-ended tip, in agreement with other reports [20, 22]. This is because radially-ended tips generate spherically shaped bubbles where opto-dynamic energy conversion efficiency is optimal [22], while flat-ended tips tend to generate more spheroid-shaped bubbles. This difference becomes less pronounced for smaller fiber tip diameters where bubbles become approximately spherical regardless of the fiber tip ending.

The SSP irrigation has been typically performed using the PIPS 600 µm fiber tip [14], geometrically equivalent to the Radial Sweeps600 tip. However, based on the results of the present study, the narrower Radial Sweeps400 fiber tip is even more effective and therefore appears to be a preferred choice.

On the other hand, when fiber tip longevity is of concern, the appropriate choice is the Flat Sweeps400 tip. This tip was found to exhibit the same pressure efficacy as the radially-ended tip (Fig. 8), however, it is more durable, especially when performing SWEEPS activation where the radial fiber tip's cone can get more readily damaged by the generated shock waves [24].

VI. CONCLUSIONS

Our study indicates that the combined SSP/SWEEPS® technology of the SkyPulse Er:YAG laser system has the potential to greatly simplify root canal therapy while successfully addressing the major goals of endodontic irrigation.

The ability of SSP/SWEEPS® to three-dimensionally debride and decontaminate dentinal tubules thus allows the clinician to effectively deliver treatments in less time and with less need to enlarge the canal system, allowing for a more minimally invasive preparation.

NOTES

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

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