Insights into passive ultrasonic irrigation

Jiang, L.M.

4

An evaluation of the effect of pulsed ultrasound on the cleaning efficacy of passive ultrasonic irrigation

This chapter has been published as: Jiang LM, Verhaagen B, Versluis M, Versluis Michel, Cuckovic D, Zangrillo C, van der Sluis LW. An evaluation of the effect of pulsed ultrasound on the cleaning efficacy of passive ultrasonic irrigation. J Endod. 2010 Nov;36(11):1887--1891

Abstract

Introduction: Multiple activations of the irrigant by using pulsed ultrasound may enhance the removal of dentin debris due to repeated acceleration of the irrigant. The aim of this study was to evaluate the effect of pulsed ultrasound on passive ultrasonic irrigation (PUI) in its ability to remove artificially placed dentin debris from a simulated apical oval extension within standardized root canals. **Methods:** Each of twenty *in vitro* root canal models with a standard groove in the apical portion of one canal wall filled with dentin debris received PUI repeatedly, either without pulsation (group1) or with pulsation (730 ms ON / 100 ms OFF in group 2, 400 ms ON / 400 ms OFF in group 3 and 100 ms ON / 670 ms OFF in group 4), corresponding to duty cycles of 100%, 88%, 50% and 13%, respectively. After each irrigation procedure, the amount of dentin debris in the groove was evaluated by taking photographs of the groove and scoring. The irrigation procedures were also visualized *in vitro* using high-speed imaging performed in glass root canal models. **Results:** The debris score was significantly lower only in group 3 (P=0.023). The *in vitro* visualization showed increased streaming and cavitation during the start-up phase of each pulse. **Conclusions:** PUI with a pulsation pattern of 400 ms ON / 400 ms OFF and a duty cycle of 50% is more effective in removing dentin debris from a simulated apical oval extension in standardized root canals than continuous ultrasonic activation. Duty cycles of 13% and 88% showed no difference compared to continuous oscillation.

Introduction

After the completion of a standard root canal preparation, the debridement of the root canal is however by far complete, leaving large untouched areas which may harbor tissue or dentin debris, microbes, and their by-products (1-7). The root canal system has better access for cleaning by an irrigant after finishing the instrumentation and, irrigation has a better possibility for cleaning the space beyond the prepared canal (8). A final rinse after the completion of the preparation is therefore an essential part of root canal debridement.

It has been realized in recent years that irrigation dynamics play an important role in the cleaning process (9-11). The use of a file in conjunction with an (ultra)sonic device that activates the irrigant has been proposed for the final rinsing step to enhance the cleaning of the root canal through streaming and cavitation (12-15).

Laser-activated irrigation has been shown to be more effective in removing dentine debris from the apical part of the root canal than PUI (16). This improvement in cleaning efficacy may be associated with the fact that the irrigant becomes accelerated at every laser pulse (16). Similarly, the acoustic streaming of the irrigant introduced by the ultrasonic activation may also be enhanced by repeated activations after introducing ultrasound pulsations into the system. Each activation causes an acceleration of the irrigant and the governing fluid physics laws link acceleration to force. In addition, pulsed ultrasound has a direct effect on acoustic cavitation in a liquid (17-19). This study therefore looks into the enhancement of the cleaning efficacy of PUI by pulsed ultrasound, under the hypothesis that PUI with pulsation is more effective than without pulsation within 10 seconds.

Materials and Methods

Dentin debris removal model

Straight roots from 20 extracted human maxillary canines were decoronated to obtain uniform root sections of 15 mm. The roots were embedded in self-curing resin (GC Ostron 100, GC Europe, Belgium) and then bisected longitudinally through the canal in mesio-distal direction with a saw microtome (Leica Microsystems SP1600, Wetzlar, Germany). The surfaces of both halves were ground successively with 240-, P400- and 600-grit sandpaper, resulting in smooth surfaces on which only little of the original root canal lumen was left. Four holes were drilled in the resin part and the two halves were reassembled by four self-tapping bolts through the holes (9). All the models were checked if there was any leakage of liquid or gas apically or laterally before experiments. If there was any, rubber dam caulk would be applied to ensure the root canal space of the model a closed system.

New root canals were prepared by K-files #15/.02 (Dentsply Maillefer, Ballaigues, Switzerland) and HERO 642 (MicroMega, Besançon, France) nickel-titanium rotary instruments to a working length (WL) of 15 mm, ISO size 30 and taper 0.06 resulting in standardized root canals. During preparation, the canals were rinsed with 1 mL of 2% NaOCl after each file, delivered by a 10 mL syringe (Terumo, Leuven, Belgium) and a 30-gauge needle (Navitip, Ultradent, South Jordan, UT, USA).

A standard groove of 4 mm in length, 0.5 mm deep and 0.2 mm wide, situated at 2 to 6 mm from working length (20), was cut in the wall of one half of each root canal with a customized ultrasonic tip. A periodontal probe with an adapted 0.2 mm wide tip was used to verify the dimension of each groove during and after preparation. The dimension of the groove is comparable to an apical oval root canal (21). Each groove was filled with dentin debris, which was mixed with 2% NaOCl for five minutes, to simulate a situation in which dentin debris accumulates in uninstrumented canal extensions (20). This model was introduced to standardize the root canal space and the amount of dentin debris present in the root canal before the irrigation procedure, to increase the reliability of the dentin debris removal evaluation. The methodology has been shown to be sensitive and the data are reproducible (22). A pilot study has shown that a single model could be reused at least 8 times without any visible defect on the surface of the canal wall. Therefore the 20 models were used repeatedly in the five experimental groups which are shown in Table 1.

Irrigation Procedure

Specimens in all the experimental groups were rinsed with 2 mL irrigant (2% NaOCl) using 10 mL syringes with 30-gauge needles (Navitip) placed 1 mm from WL, and the flow rate was approximately 5ml/min. Then the irrigant was activated by an ultrasonic file #20/.00 (IrriSafe, Acteon, Merignac, France) for 10 seconds, without (group 1) or with (groups 2-4) pulsed ultrasound (Table 1). All the experimental specimens received 2 mL irrigant which was delivered again by a syringe as final flush.

Every attempt was made to keep the file centered in the canal to minimize contact with the canal walls (*passive* activation). The file was driven at power setting ‘yellow 4’ by a piezoelectronic unit (Suprasson PMax, Satelec, Acteon) of which the footswitch was replaced by a customized pulse generator to be able to oscillate the file with pulsation.

Image evaluation and statistical analyses

Before and after each irrigation procedure, the root halves were separated and the grooves were viewed through a stereomicroscope (Stemi® SV6, Carl Zeiss, Göttingen, Germany) using a cold light source (KL 2500 LCD, Carl Zeiss). Controls verified that no debris had fallen out of the groove during the assembly or disassembly process. Pictures were taken with a digital camera (Axio Cam, Carl Zeiss). The sequence of all the pictures was randomized, and two calibrated examiners were blind to the group assignment.

The debris left in the groove after irrigation was scored independently by the two calibrated dentists using the following score system: 0: the groove is empty; 1: less than half of the groove is filled with debris; 2: more than half of the groove is filled with debris; 3: the complete groove is filled with debris (20). The percentage of inter agreement should be more than 95%; if this percentage was lower than 95%, a consensus had to be reached.

The differences in debris scores between the groups were analyzed by means of the Kruskal-Wallis test and the Mann-Whitney test. The level of significance was set at $\alpha = 0.05$.

High speed imaging experiments

An optical setup was constructed in order to visualize the effect of pulsed ultrasonic activation in the two glass models of the root canal. Both models contain straight root canals of length 10 mm, an apical diameter of 0.30 mm and a taper of approximately 0.06. One model had no side canals; the Irrisafe file (#20/.00) was positioned at 3 mm from the apex. The other model had one side-canal with a diameter 0.2 mm, located at 2.0 mm from the apex; the Irrisafe file was positioned at 1 mm from the apex. The file was driven in both models under the same conditions as the *in vitro* experiments. The root canals were filled with 5% NaOCl, to which small hollow glass spheres (mean diameter 11 µm; Sphericel, Potters Industries, UK) were added in order to track the fluid movement.

A zoom microscope with 1.25x to 20x magnification was used (BX-FM, Olympus, Japan) for magnification. The root canal was illuminated in bright-field by a continuous wave light source (ILP-1, Olympus, Japan). Imaging was performed using a high speed camera (HPV-1, Shimadzu Corp., Japan) at a frame rate of 25,000 frames per second.

The amount of activity due to an oscillating file is determined from the recordings for each pulsation scheme. Movement of the particles in the fluid, file movement or cavitation bubbles cause one frame to be different from the previous frame of the recording, and this difference in pixel values is taken as the activity of each frame.

Results

The two investigators differed in scoring 7 specimens; agreement was reached following discussion (κ=0.898). The number and the percentage of samples at each score rank in different groups after the irrigation procedures are presented in Table 1. Significant difference was only found between group 1 and group 3 (P=0.023). Activation of the irrigant with pulsed ultrasound with a duty cycle of 50% is more effective to remove apical dentin debris than that in the group without pulsed ultrasound.

The visualization recordings of the file oscillation and the streaming showed three different phases during one activation cycle. There was a start-up phase in the first 50 ms, a steady phase during the remainder of the pulse and a stopping phase of 20 ms after the pulse had ended. The general timeline of events during each pulsation is shown in Figure 1*A*. Figure 1*B* shows the activity at a certain distance from the apex.

During the start-up phase, the amplitude of the file oscillation was large compared to its final, steady oscillation amplitude, and consequently produced more streaming around the file than in the steady phase. The disturbance caused by the file that started its oscillation took approximately 10 ms to reach remote areas like the apex and side-canals. However, the penetration of the irrigant into the side-canal was limited to approximately 0.5 mm from its entrance (Figure 2).

Cavitation was also observed close to the tip of the file during the start-up phase, mostly generated at 0.5 mm from the tip. These bubbles occasionally split off and were transported to other locations in the root canal. Stable cavitation bubbles with a diameter of approximately 100 μm have been observed up to 0.4 mm into the side canal, where they tended to oscillate along with the file during the steady phase, thereby increasing the local streaming significantly.

During the steady phase, the file oscillations are not at a constant amplitude, except for an occasional unsteady motion, possibly due to the file being not perfectly straight. Streaming close to the apex and side-canals was very slow and barely observable at a frame rate of 25,000 frames per second. No cavitation was observed at the tip of the file. In the stopping phase, the fluid slowly came to a standstill in approximately 20 ms.

Discussion

In this study, the ultrasound device was switched ON and OFF repeatedly. The visualization experiments showed that the ON period (activation) is composed of three phases: the start-up phase, the steady phase and the stopping phase; the OFF period is a rest phase. During the first 50 ms, there is more activity at the file tip than after 50 ms; therefore this time period is called the ‘start-up phase’. Afterwards, the oscillation and the streaming become stable, called the ‘steady phase’. The two phases produce different flow patterns of the irrigant, defined as ‘unsteady streaming’ and ‘steady streaming’ accordingly. All phases would have their own, or combined, influence on the efficacy of the irrigant to remove dentin debris from the root canal due to the mechanical effect by the streaming and the chemical effect.

According to the results of the visualization experiments, there are three interesting phenomena taking place. (1) The oscillation of the file shows transient behavior due to the start-up of the file motion. This leads to an increased amplitude of the ultrasonic file tip, which in turn causes an increase of the irrigant velocity (unsteady streaming) around the oscillating file. (2) The unsteady streaming contributed majorly to the penetration of irrigant into (a small part of) the side canal. It could therefore be assumed that the irrigant would possibly penetrate into the groove of the *in vitro* model as well. (3) Cavitation was observed behind the tip of the file while no cavitation was observed during the steady oscillation of the file, suggesting that the generation of cavitation was related to the increase of amplitude during the start-up phase. As there were 12 more start-up phases in group 3 (50% duty cycle) than in group 1 (100% duty cycle), this could explain why the former removed the dentin debris more efficiently from the groove.

However, all the pulsation groups (group 2, 3 and 4) have the same number of pulsations or start-up phases, indicating that also the steady streaming and the rest phase should be considered, in order to explain the difference between these groups. For example, in group 4, there is no oscillation for 87% of the irrigation time, but the cleaning efficacy was still the same as the continuous mode or 100% duty cycle. This suggests that the extra activity during the ‘start-up phase’ could compensate for the reduced duty cycle. This finding was a confirmation of an earlier pilot experiment with the same methodology (n=12; 0.1 s ON / 0.9 s OFF).

Even more interesting is the result of group 2 (88% duty cycle), there are as many start-ups, but longer streaming, than in group 3 (50% duty cycle). However, the cleaning efficacy of group 2 is no better than group 3. This finding was also a confirmation of an earlier pilot experiment with the same methodology (n=12; 0.9 s ON / 0.1 s OFF). This suggests that also the ‘rest phase’ plays an important role.

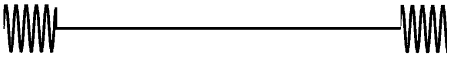
The duration of the start-up and steady phases could possibly influence the generation and dissolving of bubbles in the irrigant (18), and potential chemical effects (23) as well. As observed in the visualization experiment, stable bubbles oscillating along with the file oscillation increased the local streaming significantly. However, these bubbles typically are generated by cavitation on so-called cavitation nuclei (24), and these nuclei might dissolve during the rest phase. It is possible that a duty cycle of 50% is optimal for the reoccurrence of cavitation, again suggesting that the rest time of a pulsation scheme is also important.

Though the fluidic properties are similar between water and NaOCl (23), mechanical removal of dentin debris was better with NaOCl than water activated ultrasonically (22), suggesting that chemical effects also play a role in dentin debris removal. The duration of the activation and the rest phase could influence the chemical effects involved, which can hardly be observed by video recordings. Further studies are needed to elucidate these typical chemical aspects.

The dentin debris removal model used in this study is a closed system. The two halves of the root embedded in the resin matched perfectly and were fixed with 4 bolts well to prevent any irrigant or gas escaping apically and laterally. As the apical fluid movement mechanisms can be quite different between a closed and an open system (25), it is better to use a closed system like the model used in this study which is more clinical relevant.

The straight canals are not very commonly encountered. However, the aim of this study was to discern between the effects of the different pulsation patterns of ultrasound on the cleansing of the apical root canal. For this purpose, the model appeared adequate because of the standardization of the research procedure. Further research is needed to elucidate the effect of different root canal curvatures on the application of ultrasonic activation of the irrigant.

Table 1. Experimental groups and the number of specimens at each score rank after irrigation procedure

Group *N*=20	Pulse intervals	Schematic representation (1 second)	Duty cycle *	Score § 0	1	2	3
1	None		100%	8 (40%)	11 (55%)	1 (5%)	0 (0%)
2	730msON/ 100msOFF		88%	9 (45%)	8 (40%)	2 (10%)	1 (5%)
3	400msON/ 400msOFF		50%	15 (75%)	5 (25%)	0 (0%)	0 (0%)
4	100msON/ 670msOFF		13%	11 (55%)	5 (25%)	4 (20%)	0 (0%)
5 (control)	None		0%	0 (0%)	0 (0%)	0 (0%)	20 (100%)

* Duty cycle = length of the pulse divided by the total time of one cycle.

§ Score 0: the groove is empty; score1: less than half of the groove is filled with debris; score 2: more than half of the groove is filled with debris; score 3: the complete groove is filled with debris.

Figure 1. (*A*) Timeline of activities during one pulse of duration *T*, **(*B*)** Activity as observed on the recording of pulsation with a duty cycle of 50%. The OFF and ON period of the pulse is indicated on top of the graph. On the left is a picture of the file inside the root canal, with its oscillation pattern indicated with a red dotted line. Color indicates the amount of activity (arbitrary units). At the antinodes of the file, locations (I) and (II), there is high activity during the first 50 ms, related to the transient motion of the file and cavitation. It takes approximately 10 ms for the fluid to reach, or activity to start, at the apex or location (III). This activity disappears within 100 ms.

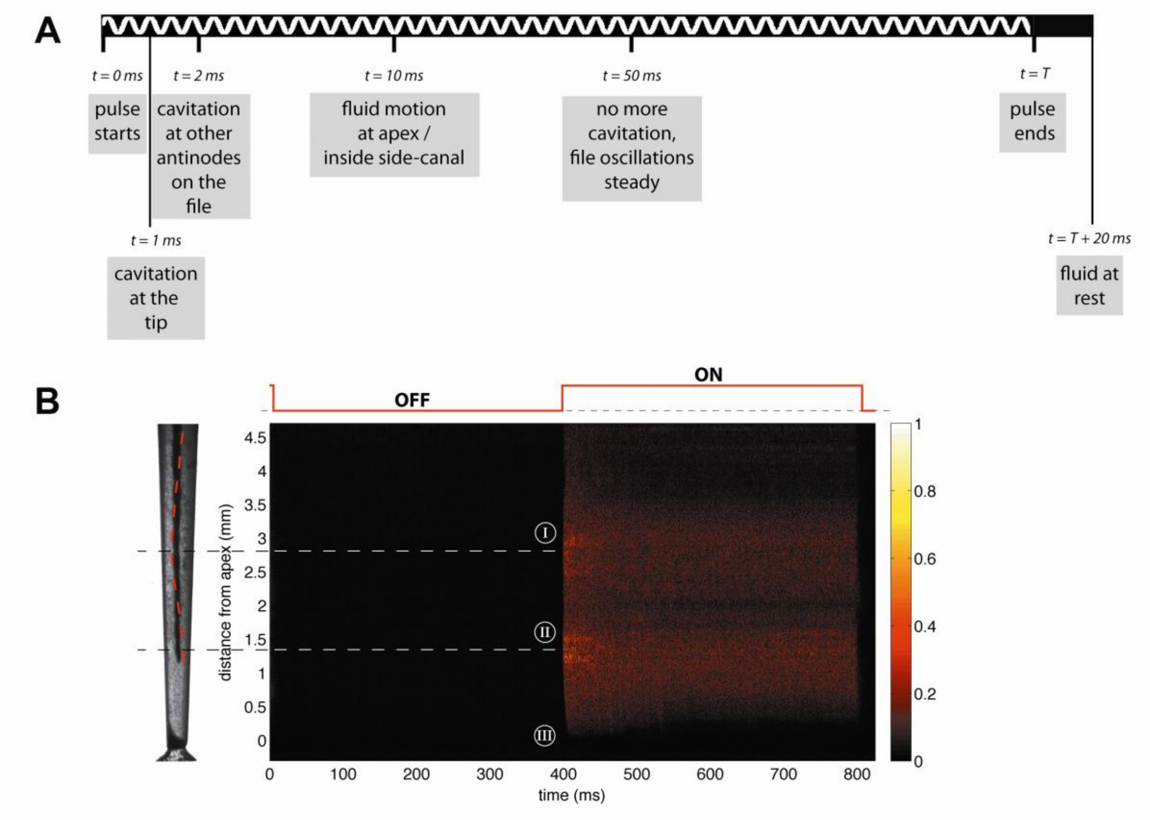
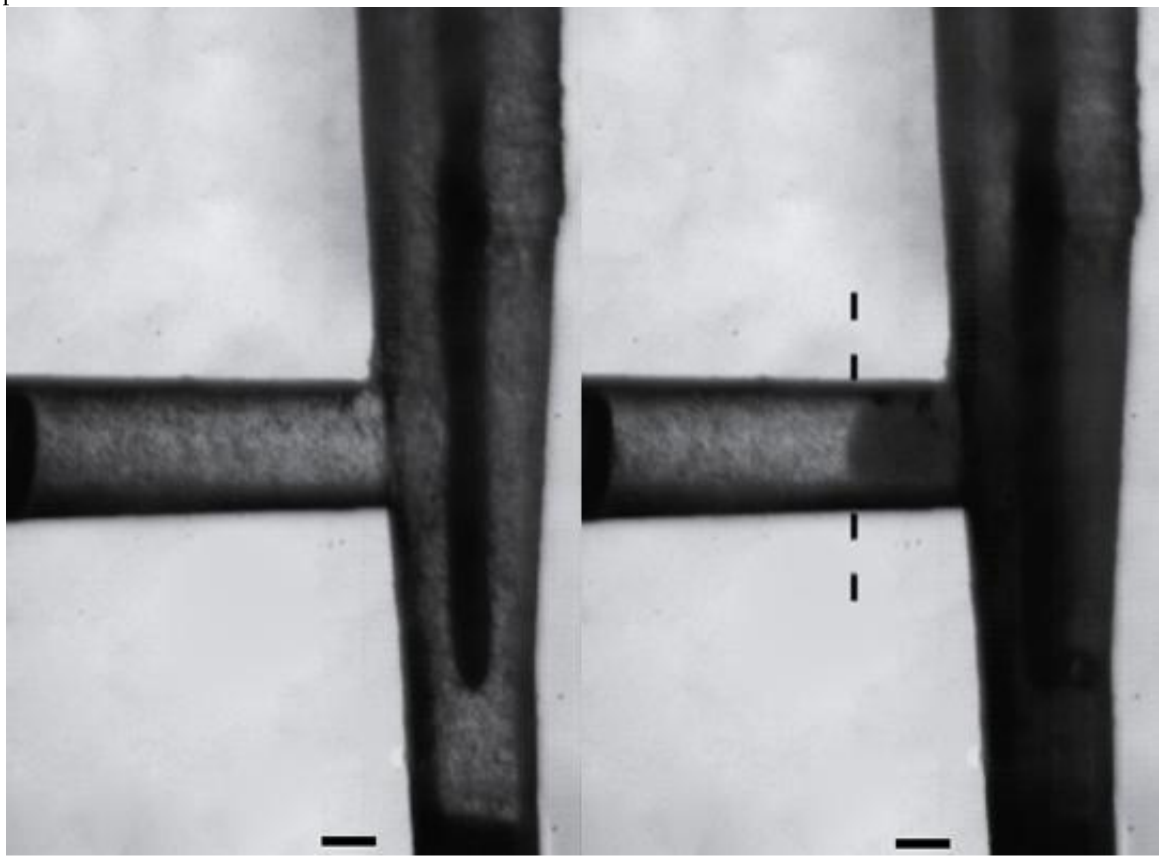


Figure 2. The root canal model with a side canal, showing the file (dark black shape) inside the main canal and the side-canal. The left panel shows the root canal before activation, with only a few particles (black dots) floating around. The right panel shows the root canal after irrigation, where the particles have been stirred up, resulting in dark areas. The dashed line shows the extension of irrigant penetration into the side canal. The black bar is 100 micrometer.



References

1. Gutierrez JH, Garcia J. Microscopic and macroscopic investigation on results of mechanical preparation of root canals. Oral Surg Oral Med Oral Pathol 1968;25:108-16.
2. Haga CS. Microscopic measurements of root canal preparations following instrumentation. J Bri Endod Soc 1968;2:41-6.
3. Walton RE. Histologic evaluation of different methods of enlarging the pulp canal space. J Endod 1976;2:304-11.
4. Wu MK, van der Sluis LW, Wesselink PR. The capability of two hand instrumentation techniques to remove the inner layer of dentine in oval canals. Int Endod J 2003;36:218-24.
5. Wu MK, Wesselink PR. A primary observation on the preparation and obturation of oval canals. Int Endod J 2001;34:137-41.
6. Schafer E, Zapke K. A comparative scanning electron microscopic investigation of the efficacy of manual and automated instrumentation of root canals. J Endod 2000;26:660-4.
7. Tan BT, Messer HH. The quality of apical canal preparation using hand and rotary instruments with specific criteria for enlargement based on initial apical file size. J Endod 2002;28:658-64.
8. Gulabivala K, Patel B, Evans G, Ng YL. Effects of mechanical and chemical procedures on root canal surfaces. Endod Top 2005;10:103-22.
9. Jiang LM, Verhaagen B, Versluis M, van der Sluis LWM. Evaluation of a sonic device designed to activate irrigant in the root canal. J Endod 2010;36:143-6.
10. Boutsioukis C, Lambrianidis T, Kastrinakis E, Bekiaroglou P. Measurement of pressure and flow rates during irrigation of a root canal ex vivo with three endodontic needles. Int Endod J 2007;40:504-3.
11. Boutsioukis C, Lambrianidis T, Kastrinakis E. Irrigant flow within a prepared root canal using various flow rates: a Computational Fluid Dynamics study. Int Endod J 2009;42:144-55.
12. Sabins RA, Johnson JD, Hellstein JW. A comparison of the cleaning efficacy of short-term sonic and ultrasonic passive irrigation after hand instrumentation in molar root canals. J Endod 2003;29:674-8.
13. Burleson A, Nusstein J, Reader A, Beck M. The in vivo evaluation of hand/rotary/ultrasound instrumentation in necrotic, human mandibular molars. J Endod 2007;33:782-7.
14. Ahmad M, Pitt Ford TJ, Crum LA. Ultrasonic debridement of root canals: acoustic streaming and its possible role. J Endod 1987;13:490-9.
15. van der Sluis LWM, Versluis M, Wu MK, Wesselink PR. Passive ultrasonic irrigation of the root canal: a review of the literature. Int Endod J 2007;40:415-26.
16. de Groot SD, Verhaagen B, Versluis M, Wu MK, Wesselink PR, van der Sluis LWM. Laser-activated irrigation within root canals: cleaning efficacy and flow visualization. Int Endod J 2009;42:1077-83.
17. Henglein. A, Ulrich. R, J. L. Luminescence and chemical action by pulsed ultrasound. J Am Chem Soc 1989;111:1974-9.
18. Lee J, Ashokkumar M, Kentish S, Grieser F. Determination of the size distribution of sonoluminescence bubbles in a pulsed acoustic field. J Am Chem Soc 2005;127:16810-1.
19. Brotchie A, Grieser F, Ashokkumar M. Effect of power and frequency on bubble-size distributions in acoustic cavitation. Phys Rev Lett 2009;102:084302.
20. Lee SJ, Wu MK, Wesselink PR. The effectiveness of syringe irrigation and ultrasonics to remove debris from simulated irregularities within prepared root canal walls. Int Endod J 2004;37:672-8.
21. Wu MK, R'Oris A, Barkis D, Wesselink PR. Prevalence and extent of long oval canals in the apical third. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2000;89:739-43.
22. van der Sluis LWM, Wu MK, Wesselink PR. The evaluation of removal of calcium hydroxide paste from an artificial standardized groove in the apical root canal using different irrigation methodologies. Int Endod J 2007;40:52-7.
23. van der Sluis LWM, Vogels MPJM, Verhaagen B, Macedo R, Wesselink PR. Study on the influence of refreshment/activation cycles and irrigants on mechanical cleaning efficiency during ultrasonic activation of the irrigant. J Endod 2010;36:737-40.
24. Brenner MP, Hilenfeldt S, Lohse D. Single bubble sonoluminescence. Rev Moc Phys 2002;74:425-84.
25. Tay FR., Gu LS, Schoeffel GJ, Wimmer C, Susin L, Zhang K, Arun SN, Kim J, Looney SW, Pashley DH. Effect of Vapor Lock on Root Canal Debridement by Using a Side-vented Needle for Positive-pressure Irrigant Delivery. J Endod 2010;36:745-50..