Sonic irrigation for removal of calcium hydroxide in the apical root canal: A micro-CT and light-coupled tracking analysis

Wonjoon Moon  
Seoul National University

Shin Hye Chung  
Seoul National University

Juhea Chang  (juhchang@snu.ac.kr)  
Seoul National University Dental Hospital

Research Article

Keywords: Calcium hydroxide, Irrigation, Light-coupling, Micro-CT, Oscillation, Sonic

DOI: https://doi.org/10.21203/rs.3.rs-537506/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Abstract

This study aimed to evaluate the efficacy of three sonic irrigation systems for removal of calcium hydroxide dressing from the apical root canal. A total of 96 single-rooted teeth in three categories of root canal curvatures (straight: 0–5°, moderate: 6–20°, and severe: > 20°) were allocated to four groups: conventional needle irrigation, EndoActivator, EQ-S, and Vibringe. The root canals were instrumented using Protaper NEXT and filled with calcium hydroxide. After removal of calcium hydroxide, the remaining volume of calcium hydroxide was measured by micro-CT analysis. Data were compared among root canal curvatures and irrigation systems using the Kruskal-Wallis test and Mann-Whitney test (p < .05). The oscillating range of each irrigation system was measured using light-coupled motion tracking. The volumes of calcium hydroxide remained in the canals of severe curvature were significantly lower than in those of straight curvature (p < .05). In the canals of moderate or severe curvature, EQ-S showed the highest removal percentage, followed by EndoActivator, Vibringe, and needle irrigation (p < .05). Light-coupled tracking showed the largest oscillating range in EQ-S (p < .05). Sonically activated irrigation systems with a flexible tip can be beneficial for cleaning of intracanal medication in the curved apical canals.

Introduction

Calcium hydroxide is the most commonly used as intracanal medicament during endodontic treatment because of its physical and biological advantages such as antibacterial effect, tissue dissolving, promoting hard tissue formation, reducing bacterial toxic products, and healing periapical tissues\(^1\). However, complete removal of calcium hydroxide is not clinically achievable, particularly in root canals with anatomical complexities\(^2\). Remnants of calcium hydroxide can hinder penetration of sealers into dentinal tubules and negatively affect sealing of canal filling materials.

For effective removal of calcium hydroxide, various technologies were incorporated as adjunctive methods to conventional needle irrigation by activating fluid movement within the canal space. Effective cleaning requires the ability to contact the irrigant in contact with the elements to be removed while not damaging the root dentin structures\(^3\). Ultrasonic devices were first introduced first in mechanical debridement in endodontics and developed into passive ultrasonic irrigation (PUI) for enhancement of intracanal debridement. PUI systems were designed so that a smooth file or wire with a noncutting tip is introduced into the canal, and energy transmission is controlled to avoid intentional contact with the canal walls. However, in a small constraint in the canal, wall contact is unavoidable and free oscillation is inhibited, particularly in the apical roots with geometrical complexities\(^4\). Consequently, risks can arise such as needle binding within the irregular dentinal walls, deforming the root canal morphology, and weakening the apical constriction\(^5\). An alternative option, passive sonic activation, incorporates non-cutting plastic tips oscillating at much lower frequencies (150–200 Hz) compared to PUI (25,000–30,000 Hz). These sonic systems attempted to avoid excessive cavitation and produce sufficient fluid agitation that removes the smear layer and dislodges intraradicular biofilm\(^6\).
Previous evaluations of activation systems for root canal irrigation have noted that the major obstacle against efficient cleaning was complicated root canal anatomy\textsuperscript{6,7}. This limited cleaning effect is more pronounced below the root canal curvature narrowing to the apical constriction. Considering the three-dimensional complexities of the apical third of the root canal system, clinical outcomes can be evaluated based on both qualitative and quantitative measurements. Several studies have focused on apical third of root canals and have introduced micro CT analysis as an outcome measurement regarding each step of clinical procedures: canal preparation and shaping\textsuperscript{8,9}, removal of previously filled materials\textsuperscript{10,11}, removal of hard tissue debris\textsuperscript{2,12}, and final intracanal obturation\textsuperscript{13,14}. The removal of the calcium hydroxide dressing during the appointment is another critical part of ensuring clinical expertise and can be clearly confirmed by 3D image construction of the root canal structures.

In this study, we applied three sonic irrigation systems for removal of intracanal calcium hydroxide and evaluated the volumes of calcium hydroxide remaining in the apical space among different root canal curvatures using micro-CT. We also measured oscillating ranges of sonically-activated irrigation tips by a light-coupled motion tracking. The null hypothesis of this study was that removal efficacy of calcium hydroxide at the apical root canal would not be affected by sonic irrigation systems.

**Materials And Methods**

**Preparation of specimens**

Ninety-six extracted single-rooted teeth with completed apices and no visible caries, cracks, or any other defects were used in the study. Institutional Review Board of Seoul National University School of Dentistry approved this study (IRB No. S-D20200031). All procedures performed in this study involving human teeth were in accordance with relevant guidelines and regulations of the institutional research committee, and informed consent was obtained from all individual participants. The teeth were decoronated and sectioned to a length of 12 mm. The root parts of the teeth were stored in 0.9 g/L thymol solution (Sigma-Aldrich, St. Louis, MO, USA). The curvatures of each root curvatures were determined in sagittal views from the micro-CT images (Skyscan 1172, Bruker, Kontich, Belgium). The scanning parameters were 100kV\(\mu\)A at the Al + Cu filter with an exposure time of 632ms. The pixel size was 30\(\mu\)m with a rotation of 0.70 and an average frame of three. The 3D images were acquired by 3D reconstruction (NRecon, Bruker, Kontich, Belgium), modeling (CTAn, Bruker, Kontich, Belgium), and 3D analysis (CTVol, Bruker, Kontich, Belgium). The curvatures were calculated with the Schneider method\textsuperscript{15}. Each of the 32 teeth was subjected to one of three categories of the canal curvatures: straight (0–5\(\degree\)), moderate (6–20\(\degree\)), and severe (> 21\(\degree\)). Specimens in each category were randomly distributed into four groups of irrigation systems: Group 1 (control), Group 2 (EndoActivator), Group 3 (EQ-S), and Group 4 (Vibringe) (n = 8/group).

**Root canal preparation and calcium hydroxide filling**
The working lengths were determined, and patency was confirmed with a #K-10 file (K-file, Maillefer Instruments, Ballaigues, Switzerland) at 1 mm short of the apical foramen. All canals were prepared with Ni-Ti files using a rotary system (X-Smart, Dentsply Maillefer, Ballaigues, Switzerland) up to the X3 file (Protaper Next, Dentsply Maillefer, Ballaigues, Switzerland), ISO size 30, and taper 0.07, resulting in standardized root canals. After canal preparation, the specimens were dried with paper points and filled with calcium hydroxide paste (Calcipex II, Nippon Shika Yakuhin, Shimonoseki, Japan), a dry cotton pellet, and a temporary restorative material (MD Temp Plus, Meta Biomed, Cheongju, Korea). The canal filling state was confirmed by the secondary micro-CT scanning. The specimens were stored at 37°C in 100% relative humidity for one week.

**Irrigation procedures**

After one week of intracanal medicament application, the temporary restorative material was removed, and calcium hydroxide was removed by one of the four protocols (Table 1). All canals were irrigated with 3% NaOCl at 2 mm short of the working length with up-and-down motions. A total volume of NaOCl used in irrigation by each protocol was 10 ml.
Table 1
Irrigation systems used in the study

| Irrigation systems | Tip characteristics | Tip sizes | Frequency | Irrigation methods |
|--------------------|---------------------|-----------|-----------|-------------------|
| Control            | Needle irrigation   | Side-vented needle (NaviTip, Ultradent Products, South Jordan, UT, USA) | 30G; straight | N/A | Canals were irrigated using a total of 10 mL of NaOCl |
| EndoActivator (Dentsply Maillefer, Santa Barbara, CA, USA) | Sonic irrigation | Flexible, non-cutting polymer tip (Dentsply Maillefer, Santa Barbara, CA, USA) | #15/.02 | 166 Hz (10,000 cpm) | Canals were irrigated using a total of 10 mL of NaOCl, applying the device three times for 20 seconds each |
| EQ-S (Meta Systems, Seongnam, Korea) | Sonic irrigation | Flexible, non-cutting polymer tip (Meta Systems, Seongnam, Korea) | #15/.02 | 217 Hz (13,000 cpm) | Same as in EndoActivator |
| Vibringe (Cavex, Haarlem, Netherlands) | Sonic irrigation | Side-vented needle (NaviTip, Ultradent Products, South Jordan, UT, USA) | 30G; straight | 150 Hz | Same as in Control |

Micro-CT analysis

The specimens were scanned using a micro-CT scanner at three time points: root curvature determination, after filling the canal with calcium hydroxide, and after removing the calcium hydroxide from the canal. The scanning parameters were the same for each three times of scans. The 3D images were acquired in the same manner at each time. The region of interest was the apical 3 mm of the root canal structure. Within the range of analysis, the volume of calcium hydroxide after filling and after removal was calculated. Percentage removal was determined according to the following equation:
Percentage removal of calcium hydroxide (\%) =

\[
\frac{\text{Volume of } Ca(OH)_2 \text{ after filling} - \text{volume of } Ca(OH)_2 \text{ after removal}}{\text{Volume of } Ca(OH)_2 \text{ after filling}} \times 100
\]

**Light-coupled tracking of oscillation**

Each irrigation system was fixed so that it could stand alone and reveal its lateral face toward the camera. The tip of each irrigation system was 90 degrees to the camera at a 20 cm distance. The tips and the camera were set at the same height. The irrigation system was activated or left as is depending on the type. Ambient light was blocked with a cloth, and blue light from the LED unit (Elipar DeepCure-S, 3M ESPE, St. Paul, MN, USA) of 1,470 mW/cm\(^2\) was shone onto the tip. As light was coupled along the tip to track its oscillating motion, its real time images were collected (Fig. 4). Also, the same images were obtained for the tip oscillating within an artificial block with a curved (10\(^\circ\)) canal. The entire procedure was repeated three times, each time with a new tip. Based on the motion traces of oscillating tips, maximum oscillating ranges were calculated with computer software (ImageJ, NIH, Bethesda, Maryland, MD, USA).

**Statistical analysis**

For the comparison of remaining volumes and removal percentages of calcium hydroxide among the irrigation systems and the root canal curvatures, a nonparametric Kruskal-Wallis test and Mann-Whitney test with Bonferroni correction were used. All statistical analyses were performed at a significance level of 0.05 using IBM SPSS Statistics software Version 26.0 (IBM, Armonk, NY, USA).

**Results**

The median percentage removal of intracanal medication from the part of apical 3 mm was shown in Table 2. In the straight canals, no significant differences existed among the groups, with all exhibiting nearly complete (100\%) removal of calcium hydroxide. In the canals with sever curvature, the percentage removal was highest in Group 3 (EQ-S), followed by Group 2 (EndoActivator), Group 4 (Vibringe), and Group 1 (control), and significant differences existed between Group 1 and Groups 2 and 3, and Group 3 and Group 4 (\(p<0.05\)). The remaining volumes of calcium hydroxide in the canals of straight or moderate curvature were not significantly different among the groups (Table 3). Instead, significant differences existed in the canals of severe curvature, in the same order as of the percentage removal (\(p<0.05\)). Graphs in Fig. 1 depicted the comparison among the different curvatures; all groups had significantly higher removal percentages and lower remaining volumes at the severe curvature compared to non-severe curvature, except Group 3 (\(p<0.05\)), which revealed no significant differences among the three curvatures.
Table 2
Median removal percentages of intracanal medication

| Groups        | Median Removal Percentage (%) | Root canal curvatures |
|---------------|-------------------------------|-----------------------|
|               |                               | Straight (A) | Moderate (AB) | Severe (A) |
| Group 1 Control | 99.95 [99.61, 100]             | 99.88 [94.55, 99.92] | 80.17 [71.05, 92.66] |
| Group 2 Endoactivator | 100 [99.93, 100]            | 99.91 [99.51, 99.99] | 99.53 [90.94, 99.84] |
| Group 3 EQ-S   | 100 [97.77, 100]              | 99.95 [99.59, 100] | 99.95 [99.38, 100] |
| Group 4 Vibringe | 100 [99.19, 100]            | 96.19 [89.10, 99.32] | 92.09 [86.21, 96.17] |

* Values with the same subscripts are not significantly different when compared within columns \((P > 0.05)\)

* Interquartile ranges [first quartile, third quartile] are shown in parentheses.

Table 3
Median remaining volumes of intracanal medication

| Groups        | Median Remaining Volume \((10^3 \text{mm}^3)\) | Root canal curvatures |
|---------------|---------------------------------------------|-----------------------|
|               |                                             | Straight (A) | Moderate (A) | Severe (A) |
| Group 1 Control | 0.83 [0, 1.84]                          | 1.34 [0.40, 63.16] | 94.60 [47.32, 156.86] |
| Group 2 Endoactivator | 0 [0, 0.12]                              | 0.42 [0.05, 1.91] | 3.18 [1.27, 30.08] |
| Group 3 EQ-S   | 0 [0, 9.99]                              | 0.36 [0, 2.30] | 0.72 [0, 1.95] |
| Group 4 Vibringe | 0 [0, 2.44]                             | 12.96 [3.18, 40.92] | 26.38 [17.84, 81.99] |

* Values with the same subscripts are not significantly different when compared within columns \((P > 0.05)\)

* Interquartile ranges [first quartile, third quartile] are shown in parentheses.
Cross-sectional micro-CT images obtained at the apical 2-mm level (Fig. 2) and 3D images (Fig. 3) exhibited calcium hydroxide remaining in the canal space. In canals with severe curvature, remnants of calcium hydroxide were noticeable at the inner and outermost part of the curvature in Groups 1 and 4.

The maximum oscillation range of each system is demonstrated in Fig. 4. The lateral extent of oscillation was measured by light-coupled tracking of movement in free space and within the artificial canal block. Group 3 exhibited the largest extent of movement, followed by Group 2, while the needle tips in Groups 1 and 4 showed minimal movement (Figs. 4 and 5a). The oscillation was restricted in the artificial block, resulting in a nearly non-existing range of movement for all groups (Fig. 5b).

**Discussion**

This study evaluated the efficacy of sonic irrigation systems for removing calcium hydroxide in the apical root canal. All three sonic systems exhibited removal capacity significantly higher than that of conventional needle irrigation. Also, free-oscillating ranges of the irrigation tips differed among the systems. The EQ-S showed the largest oscillating range and the highest percentage removal of calcium hydroxide. Therefore, the null hypothesis that removal of calcium hydroxide at the apical root canal would not be affected by the sonic irrigation systems was rejected.

Previous studies evaluating canal irrigation methods have mainly focused on removal of debris and smear layer during chemomechanical cleaning of root canal systems. When root canal treatment is extended to multi-sessional treatments, the canal space must be filled with interim medicament to induce the pharmaceutical effect. At the time of final canal obturation, the medicament should be removed to expose dentinal tubules for application and penetration of sealers. Quantitative evaluation of cleaning efficacy often is presented as percentage removal of intracanal medicament as outcome values.

Compared to the original volume of filled medication, the remaining volume was minimal, with and approximately 100% removal rate, as shown in the current study results. However, even traces of calcium hydroxide remnants adhering to the wall surface can negatively affect hermetic sealing of the intraradicular structure against microbial ingress from the oral cavity or the periapical tissues. Another consideration is that the geometry of the canal is not standardized in the pooled samples of diverse configurations. Therefore, we performed an additional comparison of the remaining volumes of calcium hydroxide among the groups. The serial images of micro-CT provided qualitative visualization and quantitative measurement of remaining calcium hydroxide. In cross-sectional images, apical canals with severe curvature resembled oval-shaped canals or an isthmus where it is difficult to access by instruments and flush out with irrigants. The three sonic systems revealed superior cleaning efficacy to conventional needle irrigation at the curved apex.

We compared three sonically activated systems with similar frequency (150–217 Hz), but different tip types: EndoActivator and EQ-S with flexible polymer tips and Vibringe with a stainless steel needle tip. EQ-S had a more flexible and softer type of polymer tip with a larger extent of movement compared to EndoActivator. When an irrigation needle or wire is incorporated into a narrow canal and vibrated,
simultaneous contacts with rigid walls are inevitable. The irrigation tip would not be freely displaced and fluid movements would be subjected to frictional forces between a boundary and vibrating medium to produce acoustic microstreaming\(^{17}\). The intensity of microstreaming is related directly to the streaming velocity and displacement that is proportional to the square of the displacement amplitude of the oscillating tips\(^{3}\). EQ-S had the largest range of oscillation, relating to more enhanced streaming effect for cleaning. The stainless-steel tip used with Vibringe yielded a minimal range of transversal movement, which might be related to its lower cleaning effect at the apical portion, particularly in severely curved canals. Our speculation was that limitedly flexible metal tips, as are often used in PUI, will be more highly affected by the confined geometry of canal walls. A previous study on file-to-wall contact during PUI showed that the file hit the wall and reversed producing a low-frequency secondary oscillation (6 kHz) that seemed to have more profound impact on activation of irrigant than did its primary oscillation (30 kHz)\(^{4}\). Another mechanism of ultrasonically or sonically activated irrigation was explained as acoustic cavitation that produces pressure fluctuations and nucleates vapor bubbles.\(^{3}\) The intensity of cavitation is affected by several factors such as diameters and shapes of tips, oscillating amplitude, surrounding geometry, and properties of medium\(^{17}\). The softness and flexibility of irrigation tips seemed to be a critical part contributing to enhance vibration impact separately from the frequency and power of the oscillating instruments.

Another consideration in terms of clinical aspect is how the irrigation tip can be directed into the apical canal, particularly with narrow and curved configurations. In this study, we used single-rooted teeth, in which the tip would be more easily inserted than into multi-rooted teeth. Nevertheless, at the canal below the severe curvature, calcium hydroxide remnants were less completely washed out less completely by a rigid stainless-steel tip, although the streaming was sonically-activated sonically as with Vibringe. Even when the tip can be readily inserted into the apical canal, clinicians might be concerned about the risk of tip separation similar to that when using the NiTi rotary files in curved narrow canals. In this light, flexible polymer tips of sonic irrigation systems have a major advantage over rigid metal tips equipped in other systems.

Root canal geometry is variable based on individual anatomy of teeth. Clinical implications in endodontic research rely on representation of anatomical complexities and how relevantly specimens are assorted under experimental settings. In a systematic and critical review on measurement of root canal curvature, 3D imaging was valued over 2D microscopic evaluation to increase precision of both qualitative and quantitative measurements\(^{18}\). In evaluation of root curvature, we reviewed a stack of images from the sagittal view rotating 360\(^{\circ}\) around the tooth axis and captured the most severe angulation of images. In terms of root curvature determination, this study was based on a methodology with high accuracy. Still, to obtain highly standardized specimens, we will consider constructing root canal models with a uniform severity of curvature. Also, using a light-transmissible medium for tooth models will incorporate more easily a sonoilluminence technique to capture the oscillating modalities. These experimental setups are obtainable by current techniques of computer-aided designing and manufacturing. Enhancement of debridement and disinfection without damage to anatomical structure is a goal of activated irrigation
systems. With standardized root canal models, the integrity of radicular structures will be confirmed accurately before and after irrigation procedures. This provides another topic of interest for future studies.

Conclusion

Sonically activated irrigation systems showed increased removal capacity of calcium hydroxide in the apical root canal compared to conventional needle irrigation. EQ-S had an extended range of oscillation with a flexible irrigation tip and higher cleaning capacity at the curved apex than other sonic irrigation systems.

Declarations

Acknowledgement

The authors deny any conflict of interest related to this study.

Authors' contributions

The authors confirm contribution to the paper as follows: study conception and design: SHC; data collection: WJM; analysis and interpretation of results: WJM, SHC, and JC; draft manuscript preparation: WJM, JC; Critical revision of the article: SHC and JC; final approval of the manuscript: WJM, SHC, and JC.

References

1 Naseri, M., Eftekhar, L., Gholami, F., Atai, M. & Dianat, O. The Effect of Calcium Hydroxide and Nano-calcium Hydroxide on Microhardness and Superficial Chemical Structure of Root Canal Dentin: An Ex Vivo Study. J Endod 45, 1148-1154, doi:10.1016/j.joen.2019.06.002 (2019).

2 Silva, E. et al. Micro-CT evaluation of different final irrigation protocols on the removal of hard-tissue debris from isthmus-containing mesial root of mandibular molars. Clin Oral Investig 23, 681-687, doi:10.1007/s00784-018-2483-1 (2019).

3 van der Sluis, L. W., Versluis, M., Wu, M. K. & Wesselink, P. R. Passive ultrasonic irrigation of the root canal: a review of the literature. Int Endod J 40, 415-426, doi:10.1111/j.1365-2591.2007.01243.x (2007).

4 Boutsioukis, C., Verhaagen, B., Walmsley, A. D., Versluis, M. & van der Sluis, L. W. Measurement and visualization of file-to-wall contact during ultrasonically activated irrigation in simulated canals. Int Endod J 46, 1046-1055, doi:10.1111/iej.12097 (2013).

5 Alturaiki, S., Lamphon, H., Edrees, H. & Ahlquist, M. Efficacy of 3 different irrigation systems on removal of calcium hydroxide from the root canal: a scanning electron microscopic study. J Endod 41, 97-101, doi:10.1016/j.joen.2014.07.033 (2015).
6 Neuhaus, K. W., Liebi, M., Stauffacher, S., Eick, S. & Lussi, A. Antibacterial Efficacy of a New Sonic Irrigation Device for Root Canal Disinfection. J Endod 42, 1799-1803, doi:10.1016/j.joen.2016.08.024 (2016).

7 Robinson, J. P. et al. Cleaning lateral morphological features of the root canal: the role of streaming and cavitation. Int Endod J 51 Suppl 1, e55-e64, doi:10.1111/iej.12804 (2018).

8 Almeida, B. M., Provenzano, J. C., Marceliano-Alves, M. F., Rôças, I. N. & Siqueira, J. F., Jr. Matching the Dimensions of Currently Available Instruments with the Apical Diameters of Mandibular Molar Mesial Root Canals Obtained by Micro-computed Tomography. J Endod 45, 756-760, doi:10.1016/j.joen.2019.03.001 (2019).

9 Sousa-Neto, M. D. et al. Root canal preparation using micro-computed tomography analysis: a literature review. Braz Oral Res 32, e66, doi:10.1590/1807-3107bor-2018.vol32.0066 (2018).

10 Aksel, H. et al. Micro-CT evaluation of the removal of root fillings using the ProTaper Universal Retreatment system supplemented by the XP-Endo Finisher file. Int Endod J 52, 1070-1076, doi:10.1111/iej.13094 (2019).

11 Kırıcı, D., Demirbuga, S. & Karataş, E. Micro-computed Tomographic Assessment of the Residual Filling Volume, Apical Transportation, and Crack Formation after Retreatment with Reciproc and Reciproc Blue Systems in Curved Root Canals. J Endod 46, 238-243, doi:10.1016/j.joen.2019.11.003 (2020).

12 Yang, Q., Liu, M. W., Zhu, L. X. & 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 53, 529-538, doi:10.1111/iej.13250 (2020).

13 Li, J. et al. Micro-computed tomography evaluation of root canal filling quality with apical negative pressure. J Dent 100, 103431, doi:10.1016/j.jdent.2020.103431 (2020).

14 Pedullà, E. et al. Root fillings with a matched-taper single cone and two calcium silicate-based sealers: an analysis of voids using micro-computed tomography. Clin Oral Investig 24, 4487-4492, doi:10.1007/s00784-020-03313-5 (2020).

15 Schneider, S. W. A comparison of canal preparations in straight and curved root canals. Oral Surg Oral Med Oral Pathol 32, 271-275, doi:10.1016/0030-4220(71)90230-1 (1971).

16 Baras, B. H. et al. Novel bioactive root canal sealer with antibiofilm and remineralization properties. J Dent 83, 67-76, doi:10.1016/j.jdent.2019.02.006 (2019).

17 Roy, R. A., Ahmad, M. & Crum, L. A. Physical mechanisms governing the hydrodynamic response of an oscillating ultrasonic file. Int Endod J 27, 197-207, doi:10.1111/j.1365-2591.1994.tb00254.x (1994).
18 Hartmann, R. C. et al. Methods for measurement of root canal curvature: a systematic and critical review. Int Endod J 52, 169-180, doi:10.1111/iej.12996 (2019).

19 Căpută, P. E., Retsas, A., Kuijk, L., Chávez de Paz, L. E. & Boutsikou, C. Ultrasonic Irrigant Activation during Root Canal Treatment: A Systematic Review. J Endod 45, 31-44.e13, doi:10.1016/j.joen.2018.09.010 (2019).

**Figures**

**Figure 1**

Removal efficacy of intracanal medication in different curvatures and devices. (a) Removal percentage of intracanal medication. (b) Remaining volume of intracanal medication. *: Values are significantly different within the same irrigation devices (p < 0.05).
Cross-sectional micro-CT images at 2 mm from the apical constriction. The white mass inside the wall indicates remaining intracanal medication.
Figure 3

3D demonstration of intracanal medication within the severe curvatures after filling and after removal by different irrigation systems. Intracanal medication is designated in blue, and the region of interest (3 mm from the apical constriction) in dashed lines.
Figure 4

Light-coupled tracking of the operating irrigation tips in free-range and inside the artificial block with a curved (10°) canal.
Figure 5

Maximum oscillation widths of the light-coupled tips. (a) Maximum oscillation widths outside the canal. (b) Maximum oscillation widths inside the artificial block with a curved (10°) canal. *: Values are significantly different among the irrigation devices (p < 0.05).