Insights into passive ultrasonic irrigation

Jiang, L.M.

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The Influence of the Oscillatory Direction of an Ultrasonic File on the Cleaning Efficacy of Ultrasonic Activated Irrigation

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Abstract

Introduction: The cleaning mechanisms and characteristics of Passive ultrasonic irrigation (PUI) are not yet completely understood. The aim of this study was to investigate whether the oscillatory direction of the ultrasonically driven file had an influence on dentin debris removal from artificially made grooves in standardized root canals. **Methods:** Each of twenty *ex vivo* root canal models with a standard groove in the apical portion of one canal wall filled with dentin debris received PUI repeatedly, either with file oscillation toward the groove or with file oscillation perpendicular to the groove. After each irrigation procedure, the amount of dentin debris in the groove was evaluated by photographs of the groove and by scoring. The oscillations of the ultrasonic file were also visualized *in vitro* by using high-speed imaging at a timescale relevant to the cleaning process, order 10 μs. **Results:** A nonparametric analysis showed significantly more dentin debris reduction when the file oscillated toward the groove ($P = 0.002$). High speed imaging showed that the oscillation of the file is in a single plane resulting in high-velocity jets emanating from the file tip in the direction of the oscillations. **Conclusions:** Oscillation of the ultrasonically driven file toward the groove is more effective in removing dentin debris from the groove than oscillation perpendicular to the groove, which can be related to the fact that there is a high-velocity jet from the file tip in a single direction following the file oscillation and a relatively slow inflow in the perpendicular direction.

Introduction

As instruments used for root canal preparation can merely touch a small part of the canal, mechanical preparation by instruments does obviously not suffice for the debridement of the complex root canal system (1, 2). Irrigation has therefore been gaining increasing attention in order to improve the cleanliness of root canal systems after root canal instrumentation. Passive ultrasonic irrigation (PUI) has been suggested to be used in order to disinfect the areas beyond instruments by acoustically activating the irrigant (3-5). Acoustic streaming has been shown to be useful in cleaning the root canal system (6).

Ultrasonically powered handpieces are normally attached with an oscillating instrument and operated at a certain frequency domain of 20 to 40 kHz. Previous *in vitro* investigations have shown that oscillation of the file perpendicular to the dentin surface had a greater influence on dentin removal than an oscillation parallel to the surface (7, 8), indicating that the energy was distributed non-uniformly around the oscillating file. Lumley has demonstrated a three-dimensional streaming pattern around the ultrasonically activated files (9), while streaming occurred mainly in front of and behind the file parallel to the handpiece. In another study, Lumley found that a file oscillation directed toward oval recesses left less debris than a perpendicular oscillation (10). Despite these previous studies, a detailed description and understanding of the oscillation characteristics of ultrasonically driven files is still missing. The aims of this study were therefore 1) to investigate whether the orientation of the ultrasonically activated file had an influence on the increase of dentin debris removal from artificially made grooves simulating uninstrumented canal extensions in standardized root canals, and 2) to investigate the streaming pattern around an ultrasonically oscillating file using visualization techniques.

Materials and Methods

Dentin debris removal model

Straight roots from 20 extracted human maxillary canines were decapitated 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 (Fig. 1*A*). The root canal space of the model was ensured as 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 (11), was cut in the wall of one half of each root canal with a customized ultrasonic tip (Fig.1*B*). 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 (12). 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 (11). 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 is sensitive and the data are reproducible (13,14). A pilot study has shown that a single model could be reused up to at least 8 times without any visible defect on the surface of the canal wall. Therefore the 20 models were used repeatedly in the three 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 placed 1 mm from WL. Then the irrigant was passively activated by an ultrasonic file for 10 seconds with the oscillation perpendicular to the groove (Group 1; Fig. 2-*C1*) or toward the groove (Group 2; Fig. 2-*C2*). The ultrasonic activation was performed with a stainless steel #20/.00 file (IrriSafe, Acteon, Merignac, France) driven by an ultrasonic device (Suprasson PMax Newtron, Acteon) at power setting 'blue 4'. Every attempt was made to keep the file centered in the canal to minimize contact with the canal walls, in order to do passive ultrasonic activation. Group 3 acted as the control group, in which the ultrasonic file was inserted but not activated. All the experimental specimens received 2 mL irrigant which was delivered again by a syringe as final flush.

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 debris left in the groove after irrigation was scored independently by three 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 (11,14). 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 to visualize the oscillation of the same ultrasonically driven file used in the *ex vivo* study. In order to simulate the confinement of apical section of the root canal, a 1-mm thick aluminum plate with a hole (Φ=0.4 mm) and a 4 mm-thick plate with a hole (Φ=0.4 mm) plus a groove with the same dimensions as the *ex vivo* model were used. The plate was positioned in a water tank (dimensions 75x64x60 mm) and the ultrasonic file was centered in the hole (Fig.1*C*). Tracer particles (hollow glass spheres, Φ=11 µm, $\rho=1.1\cdot10^3$ kg/m^3; Sphericel®, Potters Industries, South Yorkshire, UK) were added to the water for flow visualization.

The flow around the oscillating file was imaged through a microscope (BX-FM, Olympus, Japan) with a magnification of 1.25 to 20×. Illumination was performed in bright-field by a continuous wave light source (ILP-1, Olympus, Japan). Recordings were made with a high speed camera (HPV-1, Shimadzu Corp., Japan) at a frame rate of 125,000 frames per second, starting two seconds after initiation of file oscillation, in order to be able to neglect transient file motion at start-up. Recordings were analyzed using a Particle Image Velocimetry (PIV) code developed in-house.

Results

The results of the *ex vivo* experiments are presented in Table 1. There is a statistically significant difference between each of the experimental groups ($p<0.0001$). When the irrigant was activated, significantly more dentin debris was removed than in the control group (no activation). Oscillation of the file toward the groove had a significantly greater influence on dentin debris removal than oscillation perpendicular to the groove ($p=0.002$).

The time-averaged flow pattern due to an oscillating file in a large water tank is shown in Fig. 2*A*. The steady part of the flow depictured here consists of two ‘jets’ in the direction of oscillation of the file. There is an inflow toward the file from the direction perpendicular to the oscillation direction. We observe an unsteady flow which is located within a distance of approximately one diameter of the file. Fig. 2-*B1* shows a close-up of the instantaneous flow pattern, while the file is moving in the direction indicated by the white arrow. In Fig. 2-*B2* we show the instantaneous flow pattern when the confinement of the root canal is included; Fig. 2-*C1* and 2-*C2* show the average flow pattern when the groove is also included. Flow velocities in the groove when the file oscillation is toward the groove are 3-5 times higher than when the file is oscillating perpendicular to the groove.

Discussion

The results show that debris was reduced significantly more by PUI when the file oscillation was directed toward the groove than when the file oscillation was perpendicular to the groove, indicating that the oscillation direction of the ultrasonic file has a great influence.

The ultrasonically driven file oscillates mainly in the direction equal to the axis of the handpiece, and a minor transverse vibration at right angles to the main one (9). Lumley has shown more effective cleaning of an oval extension in the root canal when the oscillation of the file is directed towards the oval extension (10). He proposed two explanations: [1] the streaming forces are more intense toward the oval recess and [2] the file was less likely to be constrained when it oscillated toward the recess. However, in Lumley's study, the ultrasonic file was used for root canal instrumentation; in other words, the file was intentionally in contact with the root canal wall. Therefore, the file was unable to vibrate freely; acoustic microstreaming would consequently be less intense, although it would not stop completely (15). It could be hypothesized that when oscillating toward the groove, the file could vibrate somewhat more freely, despite intentional contact with the root canal wall, resulting in more intense streaming forces towards the groove.

PUI was performed in the current study, and the experimental setup was such that contact of the file with the root canal wall was prevented for both oscillation directions. Moreover, the oscillation amplitude of the file is approximately 28 µm according to the manufacturer, which is smaller than the dimension of the root canal in the current study, thus, the file could vibrate freely whether its orientation was toward or perpendicular to the groove. Therefore, the only explanation for the different efficiency by the two ways of irrigation should be the difference in streaming of the irrigant around the oscillating file, consisting of both the streaming orientation and strength.

This streaming has been visualized with high-speed imaging. The results show a high-velocity jet from the file tip in one dimension and a slow inflow in the perpendicular direction, which could well explain the consequences for the cleaning efficacy. Streaming has been held responsible for cleaning (6), in which the direction and the velocity of the flow may be the key factors.

The flow pattern as shown in Fig. 2*A* and 2-*B1* is qualitatively similar to the flow as described theoretically by Riley (16) and Stuart (17) and confirmed experimentally by Bertelsson (18). The flow pattern with confinement, as shown in Fig. 2-*B2*, is qualitatively similar to the flow as described theoretically by Duck & Smith (19). All authors report a boundary layer close to the oscillating object, which consisted of an oscillatory and a steady component. Outside this boundary layer, only the steady component remains, visible as jets in Fig. 2*A* and 2-*C2*. In Fig. 2-*B1* and 2-*B2* it can be observed that the boundary layer is approximately 0.3 mm thick; therefore in the apical area (when the groove is still filled with debris) the flow is dominated by the oscillatory component, which causes a shear stress circumferentially. In addition to the shear stress, it is expected that there is a push-pull mechanism by which removal of debris in the oscillation direction will be enhanced. This push-pull effect is induced by the oscillation of the file.

Once (the entrance of) the groove is starting to be emptied by removal of debris, there will be space available for the jet (steady streaming component) to form when the file is oscillating toward the groove. Shear stresses developed by this jet can enhance the removal of the debris in the groove. When the file oscillates perpendicular to the groove, the jet has no space to develop; therefore the flow is again dominated by the oscillatory component and its push-pull effect. The fluid in the groove will contribute to the inflow toward the file; however, flow velocities inside the groove are smaller than when the file oscillates toward the groove and are unlikely to contribute much to the removal of debris from the groove.

In the studies by Riley, Stuart, Bertelsen and Duck & Smith, a cylindrical file was considered whereas the Irrisafe file used in this study has a square cross-section, twisted along the length of the file. This difference in cross-section may explain the increased divergence of the measured jet compared to the theoretical solution by Smith & Duck. Experiments performed by Kim & Troesch (20) and Tatsuno (21) using square cylinders showed a flow pattern more similar to the flow pattern observed in this study.

The *ex-vivo* 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 by the 4 bolts well to prevent any irrigant flow apically nor laterally (Fig. 1*A*). As the apical fluid movement mechanisms can be quite different between a closed and an open system (22), it is better to use a closed system like the model used in this study which is more clinical relevant.

TABLE 1. Experimental Groups and the Number of Specimens at Each Score Rank after Irrigation Procedure

Group (N = 20)	Orientation of file oscillation	Irrigant	Intensity	Total duration (sec)	Score 0	Score 1	Score 2	Score 3
1	Perpendicular to the groove	NaOCl	Blue 4	10	10 (50%)	9 (45%)	1 (5%)	0 (0%)
2	Toward the groove	NaOCl	Blue 4	10	19 (95%)	1 (5%)	0 (0%)	0 (0%)
3 (control)	N/A	NaOCL	0	10	0 (0%)	0 (%)	0 (0%)	20 (100%)

Score 0, the groove is empty; score 1, 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*) Schematic representations of the standardized root canal model, its groove (*B1*) and cross section (*B2*). (*C1*) Drawing of the optical setup, showing the file inserted into the hole in the aluminum plate (details in *C2*), which is in turn inserted into a large water tank. The camera is positioned on the left, looking toward the hole. (This figure is available in color online at www.aae.org/joe/.)

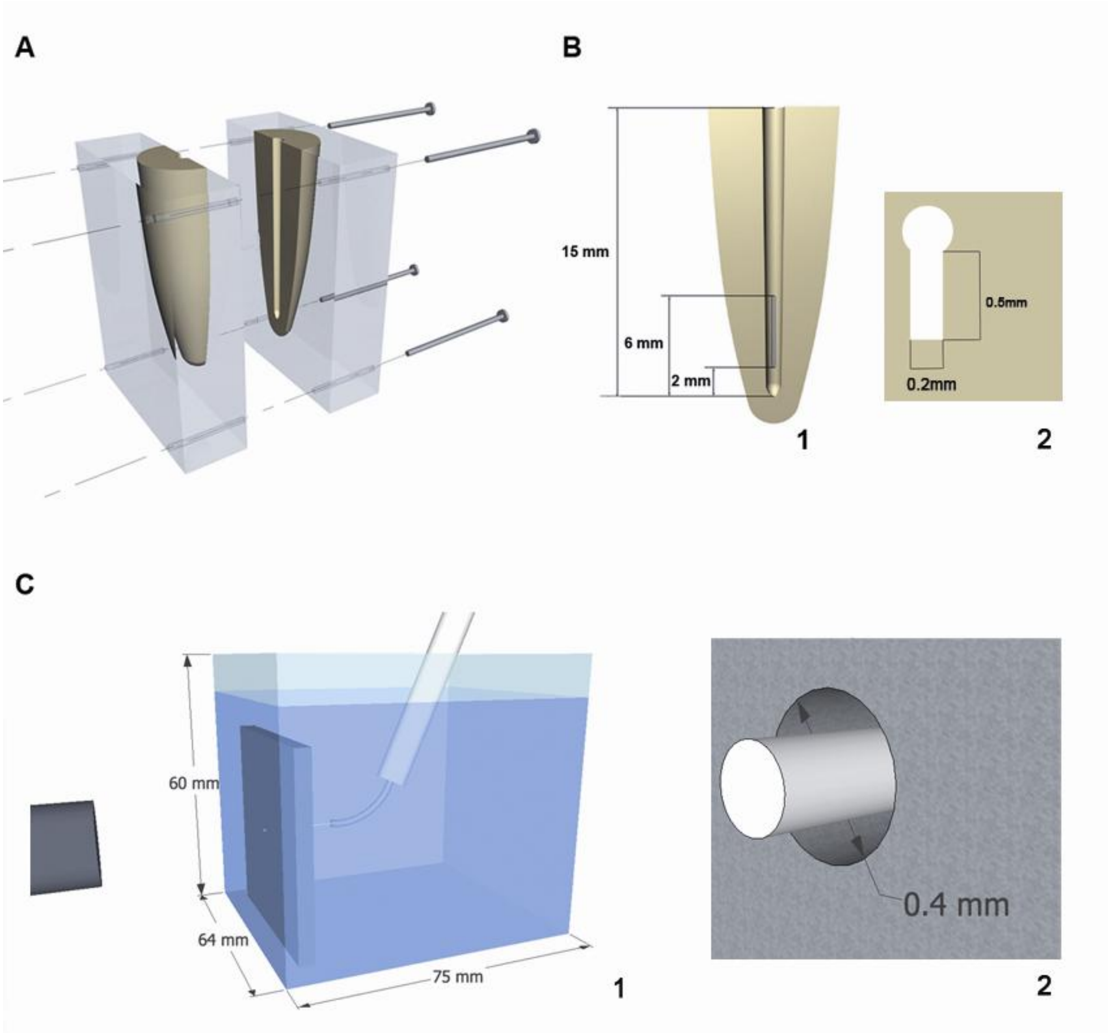
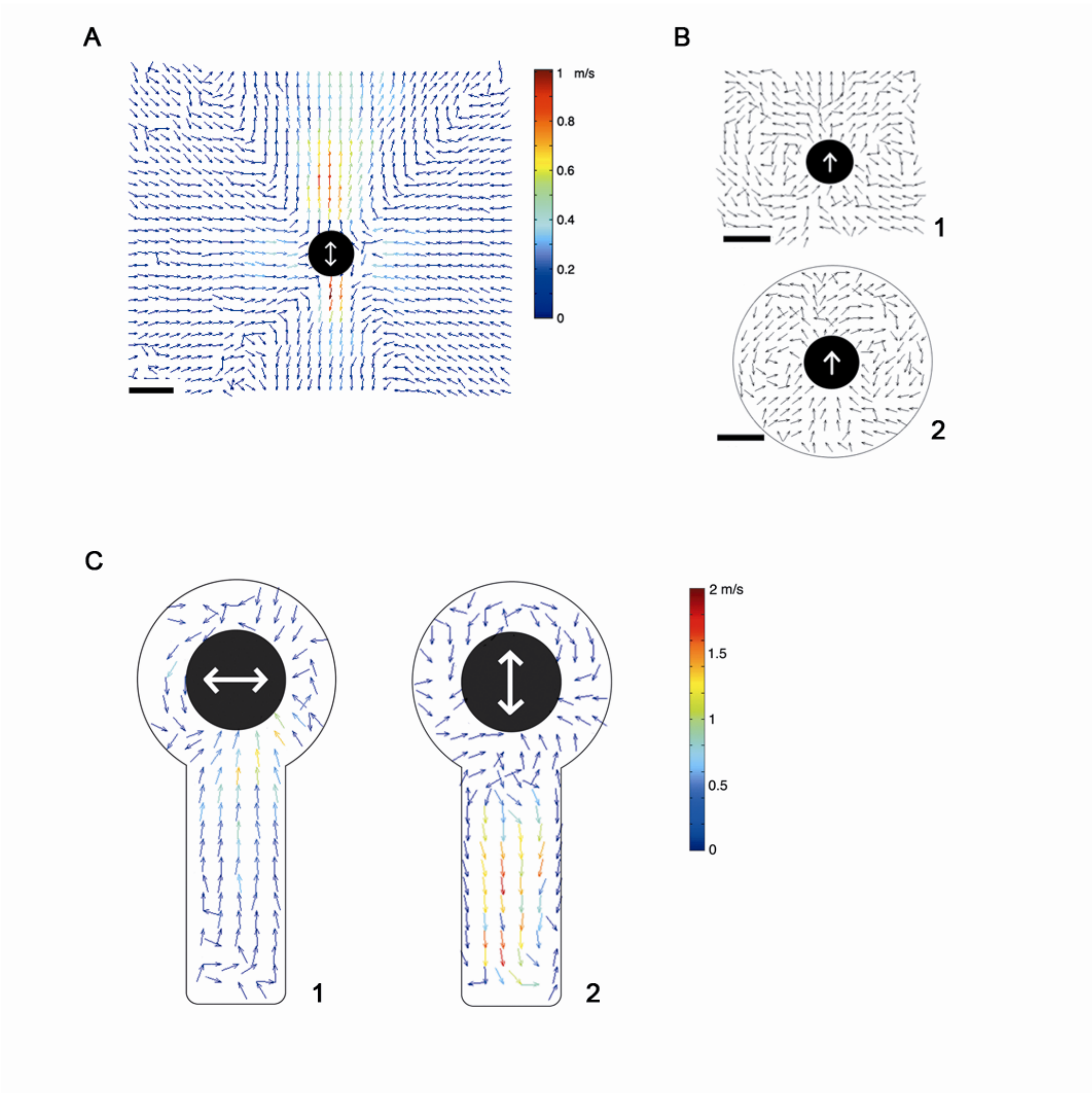


Figure 2. Direction (solid arrows) and magnitude (colors) of the flow caused by an ultrasonically oscillating file. White arrows in the black circles indicate the direction of oscillation. (*A*) Steady part of the flow when oscillating in a large water tank, averaged over 100 frames (0.8 ms). (*B1*) Unsteady part of the flow, single frame only; (*B2*) unsteady part of the flow in the confinement of a root canal, single frame only. (*C*) Sketch of the cross section of the root canal indicating the direction of oscillation with respect to the groove and the flow around the oscillating file; (*C1*) oscillation perpendicular to the groove, (*C2*) oscillation toward the groove. (Black bar is 0.2 mm.) (This figure is available in color online at www.aae.org/joe/.)



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