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Measurement and visualization of file-to-wall contact during ultrasonically activated irrigation in simulated canals

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Abstract

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Aim (i) To quantify in a simulated root canal model the file-to-wall contact during ultrasonic activation of an irrigant and to evaluate the effect of root canal size, file insertion depth, ultrasonic power, root canal level and previous training, (ii) To investigate the effect of file-to-wall contact on file oscillation.

Methodology File-to-wall contact was measured during ultrasonic activation of the irrigant performed by 15 trained and 15 untrained participants in two metal root canal models. Results were analyzed by two 5-way mixed-design ANOVAs. The level of significance was set at $P < 0.05$. Additionally, high-speed visualizations, laser-vibrometer measurements and numerical simulations of the file oscillation were conducted.

Results File-to-wall contact occurred in all cases during 20% of the activation time. Contact time was significantly shorter at high power ($P < 0.001$), when the file was positioned away from working length ($P < 0.001$), in the larger root canal ($P < 0.001$) and from coronal towards apical third of the root canal ($P < 0.002$), in most of the cases studied. Previous training did not show a consistent significant effect. File oscillation was affected by contact during 94% of the activation time. During wall contact, the file bounced back and forth against the wall at audible frequencies (ca. 5 kHz), but still performed the original 30 kHz oscillations. Travelling waves were identified on the file. The file oscillation was not dampened completely due to the contact and hydrodynamic cavitation was detected.

Conclusion Considerable file-to-wall contact occurred during irrigant activation. Therefore, the term 'Passive Ultrasonic Irrigation' should be amended to 'Ultrasonically Activated Irrigation'.

Keywords: cavitation, endodontic treatment, file-to-wall contact, oscillation, passive ultrasonic irrigation, ultrasonically activated irrigation.

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Introduction

Irrigation of root canals with antimicrobial solutions is considered an essential part of root canal treatment (Haapasalo *et al.* 2005), relying both on the mechanical cleaning action and the chemical ability of irrigants to kill bacteria, disrupt biofilm and dissolve tissue remnants (Gulabivala *et al.* 2005). Irrigant activation methods employing oscillating instruments

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are commonly used (Dutner *et al.* 2012), in order to augment debridement and elimination of microorganisms achieved by conventional syringe irrigation (Ahmad *et al.* 1987b, van der Sluis *et al.* 2007).

Ultrasonic activation of irrigants by a smooth instrument, without simultaneous instrumentation of the root canal, was first described by Weller *et al.* (1980); however, intentional contact with the wall was advised in that study. Subsequent studies highlighted the possibility of oscillation damping due to the file-wall contact, which could affect root canal debridement (Ahmad *et al.* 1987b, Walmsley & Williams 1989). A 'passive activation' technique, without any intention to instrument, plane or contact the canal walls with the file, was therefore proposed (Jensen *et al.* 1999), as opposed to earlier 'active' ultrasonic preparation techniques that combined instrumentation and irrigation (van der Sluis *et al.* 2007). The former technique is frequently described as Passive Ultrasonic Irrigation or PUI (van der Sluis *et al.* 2007).

Despite the fact that intentional contact between the ultrasonic file and the root canal wall is not currently recommended during ultrasonic activation, unintentional contact may occur due to the dimensions and complex geometry of the root canal system (Vertucci 2005). Apart from damping of the file motion and reduction of the cleaning efficacy (Ahmad *et al.* 1987a,b, Walmsley & Williams 1989), such contact could also lead to uncontrolled removal of dentine (Lea *et al.* 2009). However, to date, the file-to-wall contact during ultrasonic activation or its effect on file oscillation have not been fully evaluated.

The aims of the present study were: (i) To quantify in a simulated canal model the file-to-wall contact occurring during ultrasonic activation of the irrigant and to evaluate the effect of root canal size, file insertion depth, ultrasonic power, root canal level and previous training in this method. (ii) To investigate the effect of file-to-wall contact on the file oscillation using high-speed imaging, laser vibrometry and computer simulation.

Materials and methods

Measurement of the file-to-wall contact

Two straight metal root canal models were manufactured (Fig. 1) by cutting a frustum of a cone in a block of hardened stainless steel. This resulted in root canals with an apical size of 0.35 or 0.50 mm (ISO size 35 or 50), a taper of 6% and a length of 15 mm.

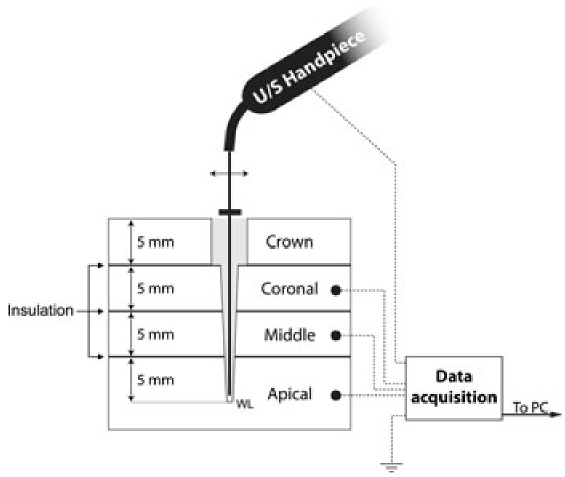

Figure 1 Schematic diagram of the metal root canal model and its electrical connections used to quantify file-to-wall contact.

Each metal block was subsequently separated into three sections, coronal, middle and apical, with a uniform height of 5 mm. An additional metal section with a cylindrical opening (diameter 4.25 mm, height 5 mm) was attached on top of the coronal section to simulate the presence of a pulp chamber. Plastic insulation layers of 0.2 mm were inserted between adjacent sections for electrical isolation. All four sections were reassembled to form a complete root canal and secured in place by plastic bolts.

Each of the three main sections (coronal, middle and apical) was connected to a high-speed data-acquisition device (USB6356, National Instruments, Austin, TX, USA) capable of simultaneously recording the voltage at each root canal level at a rate of 300 000 samples/s. A commercial ultrasound device (Suprasson P-Max Newtron; Acteon Satelec, Merignac, France) was used for irrigant activation. An electrical signal was supplied through the handpiece to the oscillating file. This signal was recorded by the data acquisition device when the file made contact with one of the root canal sections.

To test the hypothesis that previous training and regular application of ultrasonic activation of the irrigant may have an effect on the file-wall contact, measurements were conducted in two Endodontology departments. Postgraduate students in the Academic Centre for Dentistry Amsterdam, The Netherlands (ACTA group) are taught and employ ultrasonic activation during root canal treatment on a regular basis, while no such recommendation is given to the postgraduate students in the Dental School of the Aristotle University of Thessaloniki, Greece (AUTH group). In each department, fifteen postgraduate students or endodontists that had completed their training up to 5 years before the experiment volunteered to participate in the present study. Participants were blinded to the purpose of the study and the variables recorded during each experiment, and were assured that all data would be confidential. The participants' profile (gender, years of experience in dentistry, years of experience in endodontics, weekly workload in endodontics, practice limited to endodontics or not, and regular application of ultrasonic activation or not) was also recorded.

Participants were asked to perform a series of typical ultrasonic activation cycles in the metal root canals just as they would do clinically during root canal treatment. Activation was performed for 20 s using a size 20/25 mm file (Acteon Satelec) positioned at 1 or 3 mm short of working length (WL), in a size 35, 0.06 taper or size 50, 0.06 taper root canal, and at either low ('Green 4') or high ('Yellow 4') power. The insertion depth was marked by a rubber stop on the file. Silicon oil (Brookfield, Middleboro, MA, USA) with a density of 0.915 g/cm^3 and a viscosity of 5 mPa·s was used as irrigant because of its non-conductive and non-corrosive properties. All experiments were performed in triplicate. No feedback on the participants' performance was provided during or after the experiments. Each participant was also asked not to discuss his/her experience with other participants until all the experiments were completed.

Voltage measurements were subsequently analyzed in MATLAB R2011 (The MathWorks, Natick, MA, USA). The signal from each root canal section was compared to the supplied signal on the file; a difference of <5% (noise level) was noted as contact between the file and the root canal wall. The proportion of activation time (20 s) during which the file was in contact with the root canal wall (*contact time*) was calculated for each root canal section. The signal from each root canal section was also filtered by calculating the Root-Mean-Square (RMS) value for each set of 1000 data points; when the RMS value was above a threshold (half of the supplied signal on the file) the file oscillation was considered to be affected by a previous wall contact. The proportion of activation time (20 s) during which the oscillation of the file was affected by a previous contact with the root canal wall (*contact-affected time*) was calculated for each root canal section.

Statistical analysis

The effect of *root canal size*, *file insertion depth*, *ultrasonic power*, *root canal level*, and *dental school* on the contact time and the contact-affected time during ultrasonic activation were analyzed by two separate 5-way mixed-design ANOVAs. Sphericity of the within-subjects data was evaluated by Mauchly's test and equality of error variances of the between-subjects data was assessed by Levene's test. In cases that the data violated the sphericity assumption, the Greenhouse-Geisser correction was applied to the degrees of freedom. The null hypothesis was that *root canal size*, *file insertion depth*, *ultrasonic power*, *root canal level*, and *dental school* have no significant effect on the contact time or on the contact-affected time. Tukey's Least Significant Difference *post-hoc* test was employed for pair-wise comparisons. Correlation between participant characteristics and contact time or contact-affected time was evaluated by Pearson's correlation coefficient r and point-bisserial correlation. The level of significance was set at $P < 0.05$. Bonferroni correction for multiple comparisons was applied to this level where appropriate. Statistical analysis was performed using SPSS 15.0 (SPSS Inc, Chicago, IL, USA).

File oscillation characteristics during wall-contact

High-speed imaging

A high-speed camera (HPV-1; Shimadzu Corp, Kyoto, Japan) recording at a speed of 250 000 frames/s was attached to an optical microscope (BX-FM; Olympus, Tokyo, Japan) with 10 × magnification. Illumination was provided in bright-field mode by a continuous-wave cold light source (ILP-1; Olympus). A size 15/21 mm K-file (Acteon Satelec) was driven by a commercial ultrasound device (Suprasson P-Max Newtron; Acteon Satelec) at low ('Green 4') or high ('Yellow 4') power setting. The file was placed near a hard plastic wall inside a water bath (dimensions 75 × 62 × 117 mm), at an angle of approximately 5° with respect to the wall. The file was then translated in steps of 50 μm towards the wall by a translation stage (9067M, New Focus, San Jose, CA, USA), thereby increasing the contact strength. Calibration with a precision balance (TP-3002, Denver Instruments, Göttingen, Germany; accuracy 0.01 g) showed that the contact strength (defined here as weight) for this configuration increased linearly at a rate of 6 mg/μm. File oscillation was analysed in the high-speed recordings. The oscillation frequency was obtained by tracking the file tip.

Laser-vibrometer measurements
The oscillation characteristics of the file in contact with a hard surface were also evaluated by a laser scanning vibrometer, similarly to a previous study (Verhaagen *et al.* 2012). A size 15/21 mm K-file (Acteon Satelec), driven at high ('Yellow 4') power setting by a commercial ultrasound device (Suprasson P-Max Newtron; Acteon Satelec), was positioned inside a water bath (10 × 10 × 10 mm) in front of the laser scanning vibrometer (OFV-056; Polytec, Waldbronn, Germany). The file was ensured to oscillate in the scanning plane of the vibrometer. A stainless steel caries excavator was brought in contact from the side opposite to the vibrometer using a translation stage (9067M, New Focus), at the following positions denoted as distances d_c from the tip of the file: (i) No contact (control), (ii) At the tip (d_c = 0 mm), (iii) At the first antinode from the tip (d_c = 3 mm), (iv) At the middle of the working part (d_c = 8 mm), (v) At the end of the working part (d_c = 16 mm), (vi) At the driven end of the file (d_c = 21 mm). During the experiments the excavator touched the file but did not bend it. Contact was verified audibly. Approximately 50 measurement points were set up along the file where the vibrometer measured the oscillation amplitude and phase at a sampling rate of 1.5 MHz.

Computer simulation
The oscillation of the file was furthermore simulated using a previously described and validated numerical model (Verhaagen *et al.* 2012). Briefly, the one-dimensional equation of motion for a tapered beam was explicitly discretized, on a grid with a resolution of 0.25 mm and a time step of 10 ns. In order to simulate the presence of the wall, the oscillation amplitude at the point of contact was required to be positive for all times (Avanzini & van Walstijn 2004). The frequency of oscillation was obtained from the high-speed recordings. The file was assumed to be oscillating in air, thereby fluidic damping was neglected.

Results

Measurement of the file-wall contact

Contact time
Descriptive statistics for the contact time are presented in Fig. 2. The range of values was 0.04–91.6% of the activation time. Movie S1 shows a reconstruction of the contact occurring during 20 s of ultrasonic activation, based on one randomly chosen measurement. The *root canal level*-by-*root canal size*-by-*dental school* interaction was statistically significant (P = 0.022), therefore, a simple-effects analysis was performed for these three factors and the main effect of *ultrasonic power* and *file insertion depth* were interpreted. Confidence intervals (CIs) are reported as absolute differences in the percentage of activation time that the file was either in contact with the wall or affected by contact, at 95% probability.

Contact time was significantly increased when the file was positioned at 1 mm short of WL as compared to 3 mm (P < 0.001, CI: 3.68–11.32%) and at low power as compared to high power (P < 0.001, CI: 3.79–8.77%). Within the ACTA group, the contact time was significantly longer in the coronal third compared to the middle third (P = 0.001, CI: 4.23–22.31%) and in the middle third compared to the apical third (P < 0.001, CI: 3.05–12.23%), but only in the size 35 root canal. Contact time was also significantly longer in the coronal third of the size 35 root canal compared to size 50 (P < 0.001, CI: 8.44–25.30%). Within the AUTH group, the contact time was significantly longer in the coronal third compared to the middle third (P = 0.002, CI: 1.78–13.52%) and in the middle third compared to the apical third (P < 0.001, CI: 10.09–23.89%), in the size 35 root canal. However, in the size 50 root canal, the contact time was significantly longer in the coronal third compared to the middle third (P = 0.001, CI: 3.32–19.24%) but significantly shorter in the middle third compared to the apical third (P < 0.001, CI: 2.91–10.44%). Contact time was also significantly longer in the coronal and middle third of the size 35 root canal compared to the size 50 root canal [P < 0.001, CIs: 11.42–24.94% (coronal), 14.55–29.05% (middle)]. The effect of the between-subjects factor *dental school* was statistically significant only in the middle third of the size 50 root canal, where contact time for the AUTH group was shorter than for the ACTA group (P < 0.001, CI: 5.16–18.12%). All other comparisons were non-significant. No significant correlations were identified between the participant characteristics and the contact time.

Contact-affected time
Descriptive statistics for the contact-affected time are presented in Fig. 3. Overall, the range of values was 0.2–100% of the activation time. The *ultrasonic power*-by-*file insertion depth*-by-*dental school*, *root canal size*-by-*file insertion depth*-by-*dental school* and *root canal size*-by-*file insertion depth*-by-*root canal level*

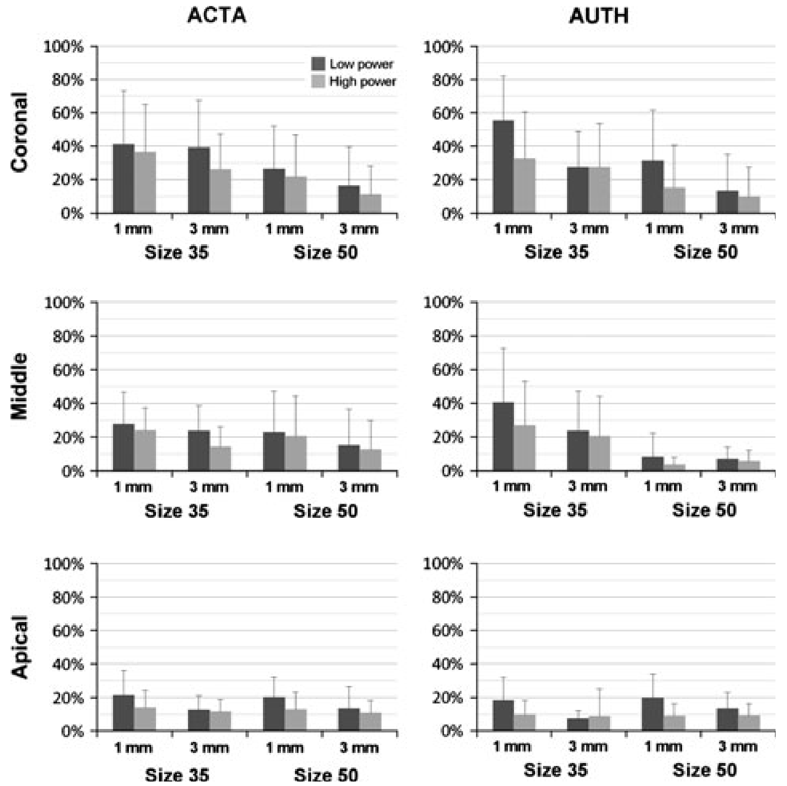

Figure 2 Contact time between the file and the wall as percentage of the activation time (20 s). Data presented as mean ± standard deviation.

interactions were statistically significant (P =0.031, P = 0.007 and P = 0.024, respectively), therefore, a simple-effects analysis was performed for these variables.

The contact-affected time was significantly shorter when the file was positioned at 3 mm compared to 1 mm, for both power levels [P = 0.001, CI: 2.61–11.07% (high); P = 0.009, CI: 1.13–10.79% (low)] and dental schools [P = 0.007, CI: 1.51–11.93% (ACTA); P = 0.008, CI: 1.28–10.88% (AUTH)]. When the file was positioned at 1 mm, the contact-affected time was significantly shorter at high power compared to low power in the AUTH group (P = 0.046, CI: 0.10–11.39%). The effect of ultrasonic power was not significant at 3 mm (P = 0.220). The effect of root canal size was significant for both insertion depths and dental schools and a longer contact-affected time was noted in the size 35 compared to the size 50 root canal [P =0.001, CI: 5.22–21.44% (ACTA – 1 mm); P < 0.001, CI: 19.30–34.44% (ACTA – 3 mm); P < 0.001, CI: 17.63 –30.25% (AUTH)]. Regarding the effect of root canal level, the contact-affected time was significantly shorter in the coronal third as compared to the middle third (P = 0.004, CI: 1.45–15.95%) and in the middle third as compared to the apical third (P < 0.001, CI: 34.54–50.76%) in the size 50 root canal, however, only the difference between middle and apical third was significant in the size 35 root canal (P < 0.001, CI: 6.41–20.77%). The effect of the between-subjects factor *dental school* was only significant when the file was positioned at 1 mm in the size 50 root canal irrespective of power (P = 0.019, CI: 1.15–22.85%) and when the file was positioned at 1 mm and activated at high power, irrespective of root canal size (P = 0.031, CI: 0.14–20.52%). In these two cases the contact-affected time was significantly longer for the ACTA group compared to the AUTH group. All other comparisons were non-significant. No significant correlations were identified between the participant characteristics and the contact-affected time.

File oscillation characteristics

The high-speed visualization and the numerical model showed that the file oscillated with a frequency of 30 kHz which was the driving frequency of the ultrasonic handpiece, but occasionally hit the wall

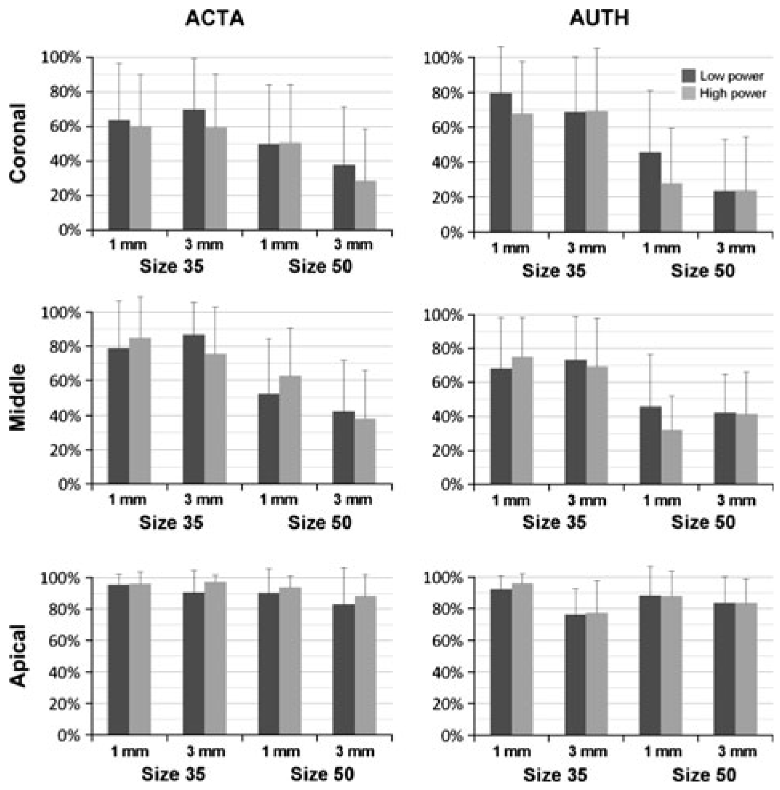

Figure 3 Contact-affected time as percentage of the activation time (20 s). Data presented as mean ± standard deviation.

and was then displaced away for several periods of the driving oscillation (Movie S2). Subsequently, the file tended to move back to the wall, causing a low-frequency secondary oscillation of the whole file (ca. 6 kHz) on top of the driving frequency of 30 kHz. An increase in contact strength did not cause a consistent reduction in the oscillation amplitude of the file tip for both low and high power, as determined by high-speed visualizations (Fig. 4). In the absence of a wall, a cloud of cavitation bubbles was observed at the tip of the file at power setting 'high'; no cavitation was visible at power setting 'low'. When the file was allowed to make wall contact, cavitation also occurred at power setting 'low' and increased for power setting 'high' (Movie S2).

Laser-vibrometer measurements showed a reduction of approximately 35% in the oscillation amplitude in all contact cases compared to non-contact, except when contact was made at the driven end of the file (Fig. 5). None of the cases studied showed complete damping of the file oscillation. In addition, contact at an antinode induced travelling waves along the file (Fig. 5). Their occurrence was verified by high-speed imaging and also observed in the numerical simulations of file oscillation. Travelling waves were not present when contact was made at a node. Additional details on the file oscillation characteristics can be found in the Appendix S1.

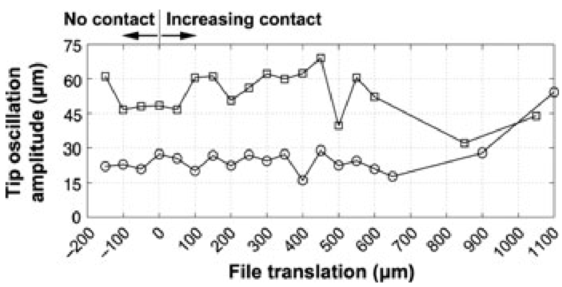

Figure 4 Oscillation amplitude of a file in single-point contact with a wall, as determined from the high-speed visualizations. The file translation on the horizontal axis corresponds to an increasing contact force at a rate of 6 mg/µm, up to 6 g at 1000 µm. The file was driven at low (circles) or high (squares) power ('Green 4' or 'Yellow 4', respectively). An increase in contact strength did not show a consistent reduction in the oscillation amplitude of the file tip.

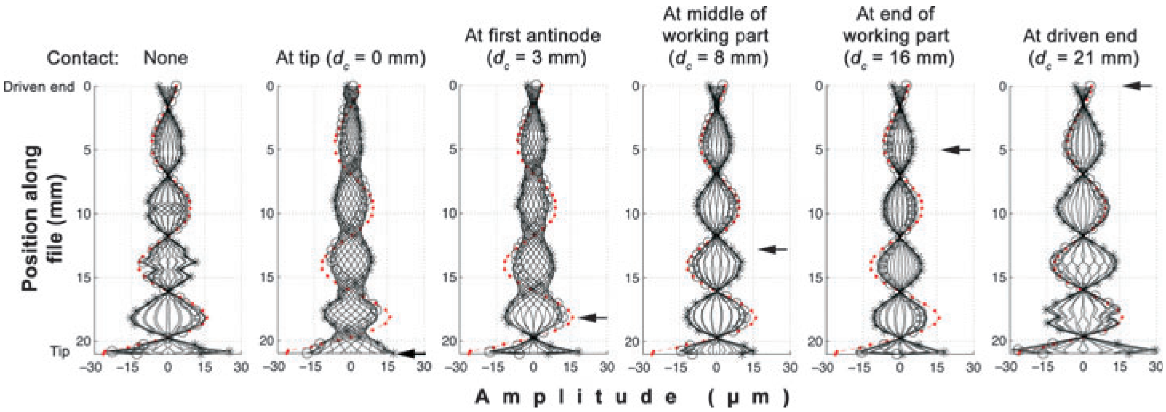

Figure 5 Oscillation patterns for a file in single-point contact with a caries excavator at different positions along its length (black arrows) as measured with the laser-vibrometer. Each line represents a 20^o phase shift; the lines for 0^o and 180^o are indicated with a circle and an asterisk respectively. The red dotted line indicates the non-contact oscillation patterns. A reduction of approximately 35% in the oscillation amplitude was noticed in all contact cases compared to non-contact, except when contact was made at the driven end of the file. None of the cases showed complete damping of the file oscillation.

Discussion

Despite the simplified root canal geometry, the immobility of the metal root canals and the optimum access, none of the 30 participants were able to avoid file-to-wall contact during the 20 s of ultrasonic activation, although sometimes the contact time was close to zero. The average contact time was approximately 20% of the activation time. However, the file was affected by contact during approximately 70% of the activation time.

No specific guidelines were given to the participants to deliberately avoid wall contact of the file. Thus, the trained participants (ACTA group) were expected to follow the taught protocol and try to avoid contact, while the non-trained participants (AUTH group) would probably apply ultrasonic activation according to their best clinical judgement. It can be argued that comparison between the two groups may have been biased. However, the purpose of this comparison was to investigate the difference between a trained and a non-trained group of clinicians, rather than the ability of the two groups to follow a specific activation protocol, therefore, balancing the groups was not an inherent requirement. The difference between the two groups was not significant in the vast majority of comparisons conducted and no specific trend could be identified. This finding indicated that previous training and regular application of ultrasonic activation did not affect the participants' performance; consequently, the initial hypothesis was disproved. It is possible that even the non-trained participants had some previous information on the purpose and method of ultrasonic activation, which is widely discussed in congresses and in the current literature. However, this is expected to be the case for any group of dentists following an endodontic training program, thus, the comparison was considered valid. None of the individual participant characteristics had a significant influence on the contact time or contact-affected time. Other characteristics that were not recorded in this study may have a more significant effect, or the dynamics that govern the file oscillation may be more important than the actions of the dentist.

The secondary oscillation was revealed during the experiments by the audible sound created when the oscillating file was in contact with the wall. This secondary oscillation can by itself introduce additional streaming but it can also affect the 30 kHz oscillation. Interference between the two frequencies may change the amplitude and velocity of oscillation and may lead to transient behaviour of the file (see Appendix S1), which has been shown to be beneficial for dentine debris removal (Jiang *et al.* 2010). The frequency of the secondary oscillation is dependent on the stiffness of the file, the contact force, the damping by the fluid viscosity and the device power setting. A stiff file will tend to move back to the wall faster than a more flexible one (Verhaagen *et al.* 2012). Thus, the secondary frequencies of the Irrisafe file (Acteon Satelec) used in the wall-contact experiments and the K-file used to evaluate file oscillation characteristics may be different. The exact value of the secondary frequency can be predicted by a simple physical model detailed in the Appendix S1.

Surprisingly, the measurements in the metal root canals showed that the contact time was significantly longer in the coronal compared to the middle and apical part of the root canal, even though the former is wider. Moreover, the contact-affected time was highest in the apical part. It can be speculated that in the apical part actual contact may occur, but due to the secondary oscillation, the file may bounce away from the wall quickly, resulting in a shorter contact time. However, during the period that the file oscillates away from the wall, oscillation is still affected by the preceding contact, so the contact-affected time is longer. In the coronal part, the file may be resting against the wall and not bouncing back and forth as much as occurred at the apical section. Another unexpected finding was the fact that a higher power setting, resulted in shorter contact time, despite the increase in the oscillation amplitude (Jiang *et al.* 2011). This finding may be also explained by the secondary oscillations. It is possible that the momentum of the file was higher at a high power setting and therefore the displacement after the collision with the wall was larger. This may have led to a lower secondary frequency and therefore a lower contact time.

The force applied to the file by the participants could not be determined with the current experimental setup. Multiple secondary frequencies associated with contact were identified in the experiments, suggesting chaotic behaviour of the file. This could be related to multiple contact points inside a root canal or travelling waves. A lack of details on the precise action of the feedback system of the ultrasound device prohibited such a calibration. Nevertheless, a simple physical model (Appendix S1) showed that the contact force is likely to affect the frequency of the secondary oscillations that are generated, as a large force applied to the file makes it oscillate back to the wall sooner than a small force. Indeed, a pilot experiment (data not shown) indicated that the contact time increased as the file was pushed against the wall with a higher force.

Laser-vibrometer measurements indicated that the oscillation amplitude may decrease due to wall contact (Fig. 5). However, both the high-speed visualizations and laser-vibrometer measurements showed that single-point contact did not result in complete damping of the oscillation for contact forces up to 6 g. This finding is at variance with the study of Walmsley & Williams (1989), but in the latter, the amount of contact force on the file was higher (up to 50 g), multi-point contact was applied and an older ultrasound device was used. It is possible that the feedback system of the current commercial devices may compensate for the increase in load, as was also concluded in previous studies (Parmar *et al.* 2011, Verhaagen *et al.* 2012). In addition, cavitation was increased by wall contact. Therefore, it is likely that acoustic streaming and hydrodynamic cavitation may still contribute to root canal cleaning. Nevertheless, multi-point wall-contact within a curved root canal as in the studies of Rödig *et al.* (2010) and Amato *et al.* (2011) or a higher contact force may have a more pronounced damping effect on file oscillation.

Damage to the dentine surface by an ultrasonic scaler (Lea *et al.* 2009) or to the bone surface by an ultrasonic surgical tip (Claire *et al.* 2012) has been related to repeated hitting by the oscillating instrument. The extent of damage on the root canal wall could not be quantified with the experimental setup used and was not within the scope of the present study. Artificial canals were manufactured by hardened stainless steel, following preliminary tests that demonstrated its ability to withstand repeated hitting by the file without visible damage, thus ensuring a constant root canal geometry in all the experiments. However, it may be speculated that the rate of damage could be associated with the secondary frequency rather than the 30 kHz driving frequency, as the file only hit the wall once per cycle of the secondary oscillation. A lower secondary frequency is therefore desirable, which can be obtained by avoiding (strong) pushing against the wall or by using a file with a lower stiffness. Damage could also be prevented by the use of files with a non-cutting cross-section (van der Sluis *et al.* 2005). Pilot experiments using optical and scanning electron microscopy confirmed that cutting in the root canal wall did not occur when non-cutting files were used without severe binding in the root canal. A higher power setting could also reduce the contact time, but in such a case the momentum of each collision with the wall would be also higher and reduced damage cannot be ensured.

A non-conductive silicon oil was used as irrigant during the experiments with the metal root canals, in order to facilitate contact measurements. However, its viscosity was 5 times higher than water and common irrigants (Guerisoli *et al.* 1998, van der Sluis *et al.* 2010), which could have increased the damping on the file oscillation; thus, the contact time may have been underestimated. Nevertheless, this effect was common for all participants and the results of the comparisons can still be considered valid.

The conditions of the present study simulated a 'best-case scenario'. More complicated root canal anatomy, uncontrolled movement of the patient and less than optimum access would probably result in even longer contact time and contact-affected time under clinical conditions. Although file-to-wall contact may still be unintentional (Jensen *et al.* 1999), its extensive occurrence renders the term 'Passive Ultrasonic Irrigation' confusing. Therefore, it is suggested that the term 'Ultrasonically Activated Irrigation' (UAI) is adopted instead to describe this method of irrigant activation.

Conclusions

Wall contact of the file during ultrasonic activation of the irrigant occurred in all cases studied. The contact time was reduced when a higher power was used, when the file was positioned further away from WL, in the larger root canal and from coronal towards apical third of the root canal in most of the cases studied. Previous training and regular application of ultrasonic activation did not show a consistent significant effect. A secondary oscillation was identified on the file during wall-contact and travelling waves were generated. The file oscillation was not dampened completely due to the contact and cavitation was detected. The term 'Passive Ultrasonic Irrigation' should be amended to 'Ultrasonically Activated Irrigation'.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. File oscillation characteristics.

Movie S1. Reconstruction of file-to-wall contact occurring during 20 s of ultrasonic activation, based on one randomly selected measurement. Contact is depicted by the red colouring of the relevant root canal level.

Movie S2. High-speed visualization of a size 20 K-file oscillating against a wall. Interference of the two frequencies and cavitation between the file and the wall can be observed. The recording speed was 250 kfps.