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Erfan Dashtimoghadam
Marquette University

Alexander Johnson
Inter Med-Vista

Farahnaz Fahimipour
Marquette University

Mohamadali Malakoutian
Marquette University

Jessica Vargas
Marquette University

See next page for additional authors

Authors
Erfan Dashtimoghadam, Alexander Johnson, Farahnaz Fahimipour, Mohamadali Malakoutian, Jessica Vargas, Jose Gonzalez, Mohamed Ibrahim, John Baeten, and Lobat Tayebi

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Erfan Dashtimoghadam
Marquette University School of Dentistry, Milwaukee, WI
Alexander Johnson
Inter Med-Vista Dental, Racine, WI
Farahnaz Fahimipour
Marquette University School of Dentistry, Milwaukee, WI
Mohamadali Malakoutian
Electrical and Computer Engineering Department, Marquette University, Milwaukee, WI
Jessica Vargas
Marquette University School of Dentistry, Milwaukee, WI

Jose Gonzalez
Marquette University School of Dentistry, Milwaukee, WI
Mohamed Ibrahim
Marquette University School of Dentistry, Milwaukee, WI
Endodontic Department, Faculty of Dentistry, Mansoura University, Mansoura, Egypt
John Baeten
Inter Med-Vista Dental, Racine, WI
Lobat Tayebi
Marquette University School of Dentistry, Milwaukee, WI

Abstract
Passive activation of endodontic irrigants provides improved canal disinfection, smear layer removal, and better subsequent sealing. Although evidence suggests that passive activating endodontic devices increase the effectiveness of irrigation, no study exists to quantitatively compare and validate vibrational characteristics and cavitation produced by different ultrasonic endodontic devices. The current study aims to compare the efficiency of various commercially available ultrasonic endodontic activating devices (*i.e.*, EndoUltra™, EndoChuck, Irrisafe™, and PiezoFlow®). The passive endodontic activating devices were characterized in terms of tip displacement and cavitation performance using scanning laser vibrometry (SLV) and sonochemical analysis, respectively. The obtained results showed that activator tip displacements and speed correlate to established cavitation thresholds. The EndoUltra™ tip speed was measured to be 14.5 and 28.1 m/s at 45 and 91 kHz, respectively, which is greater than the threshold. The EndoUltra™ was found to be the only device that exceeds the cavitation thresholds (*i.e.* tip speed and displacement), as evident from laser vibrometry analysis, and subsequently yielded measurable cavitation quantified *via* sonochemical analysis. All other passive endodontic activation devices, despite ultrasonic oscillation, were unable to produce cavitation.

Keywords
Passive endodontic activating devices, Scanning laser vibrometry, Sonochemical analysis, Cavitation, EndoUltra

1. Introduction
The chemomechanical preparation of the canal system relies on both the mechanical flushing and chemical ability of irrigants to dissolve dentinal debris and microorganisms. In order to achieve a successful root canal treatment, it is necessary to remove all vital and necrotic pulp tissues, bacteria, and other microorganism from the canal [[1], [2], [3]]. The complex anatomy of the root canal system make cleaning it very difficult, such as unreachable irregularities of the root including oval extension, isthmuses and apical deltas [4,5]. It is understood that conventional rotary instrumentation contacts only 40% of the root canal, thus, irrigation is highly important to reach untouched areas. However, standard syringe irrigation does not itself satisfactorily cleanse and debride the entire canal alone [6,7].

Energizing endodontic irrigants has been shown to result in improved irrigant reach, canal disinfection, smear layer removal, sealing, and a higher rate of root canal therapy success [[8], [9], [10], [11]]. Irrigant activation is typically achieved by applying sonic or ultrasonic energy for one to several minutes within the canal. Although some research shows sonic activation to be better than no irrigant activation, ultrasonic activation has been shown to be quicker and more efficacious due to properties unique to ultrasonics (*i.e.* cavitation and acoustic streaming) [[12], [13], [14]]. As a result, various adjunct activation/irrigation devices have been developed to improve debridement of the root canal system. Although evidence suggests that passive activating endodontic devices increase the effectiveness of irrigation [[15], [16], [17]], no study exists to quantitatively compare and validate vibrational characteristics and cavitation produced by different ultrasonic endodontic devices.

The current study aims to compare the efficiency of various commercially available passive endodontic activating devices (*i.e.*, EndoUltra™, EndoChuck, Irrisafe™, and PiezoFlow®) in terms of their respective displacement, velocity, and cavitation performance.

2. Materials and methods

2.1. Materials

Analytical grade potassium iodide (KI; Alfa Aesar, Haverhill, MA), ethanol (Amresco, Solon, OH), and carbon tetrachloride (Sigma Aldrich, Milwaukee, WI) were used as received.

2.2. Assessment of tip vibration characteristics

The vibrational characteristics of various commercially available passive endodontic activating devices (EndoUltra™ with a 20/02 tip (Vista Dental, Racine, WI), EndoChuck with an ISO size 20 file (Electro Medical Systems, Nyon, Switzerland), Irrisafe™ with an IRR20/21 tip (Satelec, Acteon, Merignac, France) and PiezoFlow® (Dentsply Sirona, York, PA)) were characterized using scanning laser vibrometry (SLV). EndoUltra™ was used as received, while the other devices were activated by means of a Piezoelectric Ultrasonic Unit (Satelec Newtron scaler) at a power level of 6. The SLV system was a Micro System Analyzer (MSA-100-3D, Polytec GmbH, PolytecPlatz, Waldbronn, Germany). Devices were orientated to ensure reproducible positioning throughout experimentation. The out-of-plane and in-plane motion was characterized in the frequency range of 27–100 kHz at the activator tips' apical point.

2.3. Sonochemical analysis

Cavitation production of passive endodontic activating devices was quantified using sonochemistry [24,25], where the conversion of potassium iodide (KI) to tri-iodide (I_3^-) was measured through spectrophotometry. In brief, 1.66 g of KI (0.5 M KI) was dissolved in 20 mL 80% ethanol in distilled water. Carbon tetrachloride was added to the KI solution at a 1:11 ratio to create the cavitation solution. 10 mm of the device tip was then inserted into the cavitation solution (500 µL) in a 96 well plate and activated for 1 and 3 min, mimicking clinically relevant activation durations. The cavitation solution was made fresh for each ultrasonic device. The absorbance of I_3^- (peak 355 nm) was measured by means of a spectrophotometric plate reader (320–440 nm wavelengths; Synergy HTX, BioTEK, Winooski, VT). Triplicate samples were obtained and analyzed.

3. Results and discussion

Tip displacement amplitudes in *x*, *y* and *z* directions of the characterized products from SLV analysis are shown in Fig. 1. The EndoChuck shows significant displacement at three frequencies of 29.5, 59, and 88.5 kHz, whereas the EndoUltra™ tip achieves significant displacement at two frequencies of 45 and 91 kHz. Analysis of the PiezoFlow® vibrational characteristics reveals minimal tip displacement (<0.25 µm) at several frequencies of 29.3, 58.6, and 88 kHz. The Irrisafe™ does not show any characteristic resonant point and oscillates with minimal amplitude (<0.6 µm) throughout the tested frequency range in all directionalities. Among the various characterized passive endodontic devices, the EndoUltra™ offers the smoothest oscillation behavior with definitive resonant points at the resonant frequency and second harmonic, which may have implications on tip longevity, as destructive oscillations are not present.

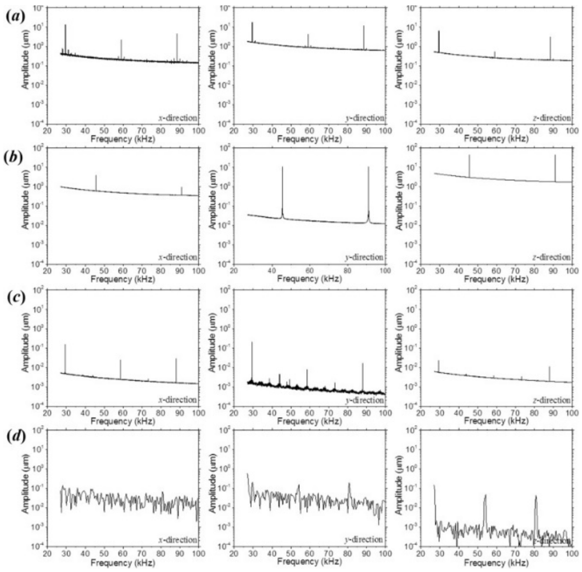

Fig. 1. Graphs of tip displacement amplitude in *x*, *y* and *z* directions of the various commercially available passive endodontic activating devices: (a) EndoChuck, (b) EndoUltra™, (c) PiezoFlow®, and (d) Irrisafe™, based on scanning laser vibrometry analysis.

For each frequency, the overall tip distance was calculated from the displacement data (Fig. 2). The threshold of total tip distance to achieve cavitation, based on Ahmad et al. [18], has been shown in the graph as a dashed line. The EndoUltra™ is the only device that exceeds the distance threshold to achieve cavitation: At 45 kHz and 91 kHz the cavitation threshold is 313 µm and 154 µm, respectively, while the EndoUltra™ has total tip distance of 319 and 154 µm, respectively. The EndoUltra™ tip speed at 45 kHz and 91 kHz, was calculated to be 14.5 and 28.1 m/s, respectively, which is greater than the 14.1 m/s threshold. The EndoChuck's max tip speed is calculated to be 7.2 m/s, while Irrisafe™ and PiezoFlow® have calculated speeds <0.12 m/s.

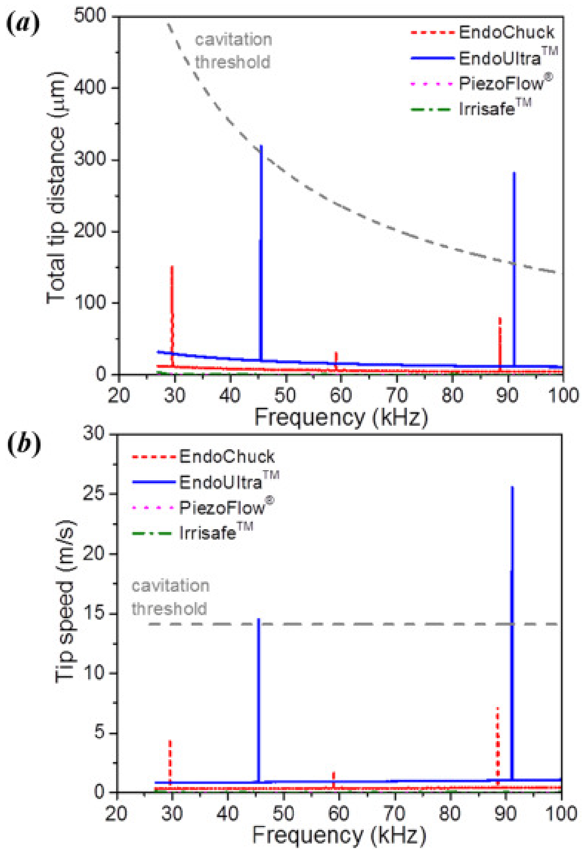

Fig. 2. (a) Total tip distance, and (b) tip speed of various commercially available passive endodontic activating devices (EndoChuck, EndoUltra™, PiezoFlow®, and Irrisafe™) throughout the test frequency range. The tip distance threshold to achieve cavitation has been shown in the graphs as a dashed line.

The UV/Vis absorption spectra of activated KI solutions are shown in Fig. 3. From sonochemical analysis, the EndoUltra™ is the only device that produces cavitation due to presence of a distinguished triiodide peak at 355 nm. As expected, increasing the activation time from 1 min to 3 min significantly increases the amount of cavitation produced and the amount of triiodide formed using the EndoUltra™ (0.62 ± 0.03 AU *vs* 0.98 ± 0.03 AU, respectively, $p = 0.0002$). The EndoChuck, Irrisafe™, and PiezoFlow® do not produce cavitation, as no peak is seen at 355 nm after 3 min activation. The absorbance visualized below 330 nm in the EndoChuck, Irrisafe™, and PiezoFlow® is an absorbance artifact from the 96 well plate.

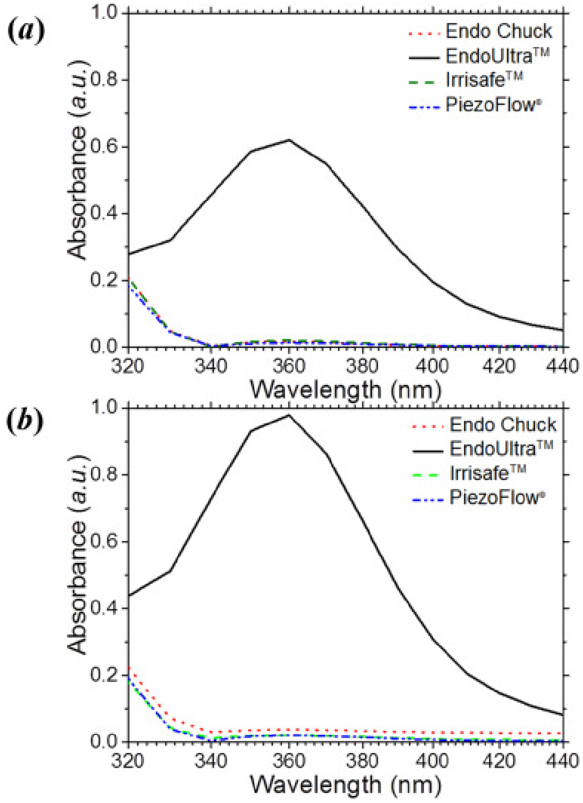

Fig. 3. The UV/Vis absorption spectra of activated potassium iodine solution by means of various commercially available passive endodontic activating devices (EndoChuck, EndoUltra™, PiezoFlow®, and Irrisafe™) for (a) one, and (b) 3 min.

Traditional needle irrigation is relatively weak and dependent on several clinical variables: depth of placement, anatomy of the root canal, and the needle type (*i.e.* slotted, open-ended, skived, *etc.*). As such, various ultrasonic activation devices have been developed to provide improved irrigation, tissue removal, better cleaning of lateral canals, and enhanced bacteria removal. Here, the authors aim to provide a quantitative comparison of the vibrational characteristics and sonochemical effects of commercially available passive endodontic activating devices, including EndoUltra™, EndoChuck, Irrisafe™ and PiezoFlow®.

Passive ultrasonic irrigation relies on the transmission of acoustic energy from an ultrasonically oscillating object to activate the irrigant in the root canal, which depending on the tip's speed, can create cavitation. Generally, cavitation is the generation and subsequent collapse of vapor bubbles in a solution due to localized pressure reductions. When ultrasound energy passes through a liquid medium, the acoustic pressure propagation produces negative pressure in the system, and consequently, overcomes the tensile strength in the liquid medium to form small cavitation bubbles. In endodontics, this change in pressure is caused by an object moving at ultrasonic frequencies within the confines of the root canal.

This study quantified cavitation potential of ultrasonic endodontic devices *via* two techniques. First, vibrational characteristics were analyzed using a Micro System Analyzer, which quantifies the tip's microstructural displacement and velocity responses by integrating a microscope with scanning laser Doppler vibrometry, and scanning white light interferometry. The SLV technique is based on measuring the Doppler shift of a laser beam that is reflected off the target surface, which results in defining the velocity and displacement of the surface regarding the incident beam. As SLV quantifies tip displacement and velocity, these results can be compared to distance and speed thresholds to create cavitation. In addition, sonochemistry was utilized to directly quantify the amount of cavitation created by ultrasonic solution activation. One of the most studied sonochemistry tests uses potassium iodide, which was utilized in this study. Briefly, hydroxyl radicals (•OH) caused by cavitation proceed to oxidize iodide ions, which then continue to react and form the triiodide (I_3^-) ion. Triiodide ions form only in the presence of cavitation, and these ions absorb strongly at a wavelength of 355 nm.

Bernoulli's equation (Eq. (1)) relates the speed (μ) required to exceed the pressure change threshold (ΔP) to achieve cavitation.

(1) $\frac{1}{2}\rho\mu^2 = \Delta P$

where ρ is the density of the fluid (assume 1000 kg/m^3 for water), and ΔP is ambient pressure plus the vapor pressure of the fluid (10^5 Pa and 2000 Pa, respectively). Solving for the speed yields 14.1 m/s. As the experimental KI sonochemistry solution's density is 9002 kg/m^3, the speed threshold required for cavitation in this media is 14.9 m/s. Although this speed is ~5% >14.1 m/s, it should be realized that less dense liquids will permit greater tip displacement for the same frequency. Therefore, tip speed will be greater in less dense liquids. However, it should be noted that this calculation does not take into consideration catalysts (*e.g.* carbon tetrachloride), which help hasten cavitation-associated reactions.

The relationship between frequency (f), tip speed (μ), and tip distance (D) is summarized in Eq. (2), where speed and tip distance are scalar quantities. The calculated threshold of tip distance to achieve cavitation at any frequency can be calculated from Eq. (2), since tip speed (μ) needs to be at least 14.1 m/s. This calculated distance threshold is shown in Fig. 2 as a dashed line.

(2) $f = \frac{\mu}{D}$

SLV experimentation provides three-dimensional displacement and velocity data which are vector quantities. The individual velocity vectors $\mathbf{V_x}$, $\mathbf{V_y}$, and $\mathbf{V_z}$, which have coordinates of (V_x,0,0), (0,V_y,0), and (0,0,V_z), respectively, provide an overall tip velocity vector $\mathbf{V_{xyz}}$ of (V_x, V_y, V_z). The tip speed, a scalar quantity, is calculated as the magnitude of vector $\mathbf{V_{xyz}}$ (Eq. (3)). Similar arithmetic needs to be completed for the SLV displacement data to obtain an overall tip distance amount (*i.e.* a scalar quantity). Individual displacement vectors ***x***, ***y***, and ***z***, which have coordinates of (*x*,0,0), (0,*y*,0), and (0,0,*z*), respectively, provide an overall displacement vector ***xyz*** of (*x*,*y*,*z*). Eq. (4) can then be used to calculate the total tip distanced traveled. The tip speed (μ) and/or tip distance (D) values from SLV analysis can be compared to calculated threshold values using Eq. (2) to hypothesize if a tip will yield cavitation when ultrasonically activated in a liquid media.

(3) $TipSpeed(\mu) = \left|\left|\boldsymbol{V_{xyz}}\right|\right| = \sqrt{(V_x^2) + (V_y^2) + (V_z^2)}$

(4) $TotalTipDistance(\mathrm{D}) = 2 * \pi * \left|\left|\mathbf{xyz}\right|\right| = 2 * \pi * \sqrt{(x^2) + (y^2) + (z^2)}$

The results of this study concluded that the EndoUltra™ is the only device that yields cavitation *via* SLV analysis and sonochemistry. Utilizing the SLV data, a velocity of 14.5 m/s and 28.1 m/s is calculated for the EndoUltra™ tip at its fundamental frequency and second harmonic frequency, respectively, which are both greater than the calculated 14.1 m/s cavitation threshold. The increased tip velocity of EndoUltra™ also infers enhanced canal cleansing *via* increased acoustic streaming and fluid turbulence. Cavitation created by the EndoUltra™ was further supported through KI sonochemical analysis at one and 3 min. Therefore, the EndoUltra™ is able to produce substantial amounts of cavitation within clinically relevant durations. Conversely, all other devices did not show any significant absorbance at 355 nm, which implies they do not produce measurable cavitation within 3 min of activation. Although this study did not focus on canal cleanliness, the superior performance of

EndoUltra™ in producing cavitation, compared with other passive endodontic activating devices, may suggest that the EndoUltra™ would be more effective for canal debridement. Conversely, the other characterized passive endodontic ultrasonic activation devices were unable to produce significant tip displacement and cavitation within the root canal space, which may attribute to lower clinical efficacy. Further studies are warranted to compare canal cleanliness and antimicrobial effectiveness of these endodontic ultrasonic devices.

It should be considered that sonic endodontic activation devices (max frequency of 167 Hz) cannot create cavitation due to the confines of the canal space (<350 μm) and subsequent tip displacement limitations (max displacement of 350 μm). Conversely, all ultrasonic tip displacements were smaller than typical canal preparations (*i.e.* 350 μm diameter), supporting that these results are translatable to clinical use.

The SLV results from this study conclude that ultrasonic tips travel in an elliptical pattern which is in agreement with Lea et al. [19,20]. Further, the measured displacement results correlate well with other researchers who show max oscillation amplitudes of 10–45 μm in one direction [21,22]. Additionally, Lea et al. previously showed through terephthalate dosimetry that cavitation formed by ultrasonic tips is dependent on tip design, geometry, and ultrasonic power [23]. Through subsequent luminol research, this group showed that cavitation correlates to vibrational antinodes of scaling tips [21], which represent the locations of greatest tip displacement. Therefore, although ultrasonic tips may be effectively driven at ultrasonic frequencies, their vibrational characteristics must exceed the necessary thresholds to yield cavitation. This concept is important for endodontology and endodontology research, as all passive ultrasonic activation/irrigation units do not perform equivalently and yield cavitation.

SLV testing was performed in free air instead of in solution, which should be recognized as a minor study limitation. Therefore, the recorded displacement measurements are likely greater than in clinical practice. Additionally, vibrational characteristics using SLV were only measured at the end of the tips, instead of characterizing oscillation characteristics and patterns along the length of the tips. However, these limitations were understood at the study's onset and, as a result, sonochemistry testing was performed in tandem to determine if activation devices yield cavitation in a more clinically relevant setting (*i.e.* activating a liquid media for 1–3 min). Based on SLV data, the EndoUltra™ should yield cavitation, which was then confirmed *via* sonochemistry testing. In summary, SLV data should not be used to independently evaluate cavitation potential, rather, SLV analysis can be used to evaluate the tip's vibrational and displacement characteristics, while more appropriate techniques can be used for cavitation quantification (*i.e.* sonochemistry).

4. Conclusion

Although evidence suggests that passive activation enhance the efficiency of irrigation, herein it was demonstrated that some ultrasonic endodontic activating devices are unable to produce cavitation within the root canal space. Scanning laser vibrometry and sonochemical analysis revealed that such deficient performance originates from inadequate tip velocity and displacement. The presented findings may have implications for improved endodontic irrigants that facilitate cavitation when assisted by the appropriate passive endodontic activation devices (*e.g.* EndoUltra™).

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