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Visualization of bubbles generation of electrical driven EndoActivator tips during solutions activation in a root canal model and a modified extracted tooth: a pilot study

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Visualization of bubbles generation of electrical driven EndoActivator tips during solutions activation in a root canal model and a modified extracted tooth: a pilot study

ABSTRACT

Background: EndoActivator, a sonically-driven canal irrigation system (Dentsply Tulsa Dental Specialties, Tulsa, OK), has been developed for activating root canal irrigants, and has recently been released onto the market.

Purpose: To obtain an initial understanding of bubbles generation of electrical EndoActivator tips during activation of the irrigant in a transparent root canal model and a modified extracted tooth.

Methods: A modified extracted tooth and a straight glass model were filled with a solution containing 17% EDTA or 3% NaOCl. A medium activator tip 22 mm polymer noncutting #25, 0.04 file driven by an electrical sonic hand-piece at 190 Hz (highest level) induced pressure waves that produced macro- and micro-bubbles. The physical mechanisms involved were visualized using a Miro 320S high-speed imaging system (Phantom, Wayne, NJ, USA) with high temporal and spatial resolutions. The imaging system acquired images at 25,000 frames per second with 320Å~240 pixels per image, and attached a 60 mm f/2.8 macro lens (Nikon, Tokyo, Japan).

Results: The end of the tip did not generate bubbles formation. Disruption of surface tension at the air–solution system in the glass canal model by an electrical sonic driven EndoActivator tip generated bubbles in the solution. However, it did not occur at the system of solution–air interfaces in the glass canal and modified extracted tooth.

Conclusion: The physical mechanism of the solution activated by an electrical sonic driven EndoActivator tip in **generating** bubbles formation is because the surface tension at the air–solution system disruption. No bubbles formation occurred in the solution in the restricted space either is the solution-air system or modified extracted tooth.

Clinical Relevance: Better understanding of the physical mechanisms that relate specifically to the activation behavior of EndoActivator tips in solutions is key to improving the cleaning mechanism that applies during root canal treatment.

Keywords: bubbles formation; EndoActivator; endodontics; sonic

Introduction

Non-automated agitation of the irrigant can be produced using a file¹ or a gutta-percha cone² inserted in the shaped and cleaned canal subsequently moved periodically and rapidly by the operator. Electrical ultrasonic and sonic devices are examples of automated agitation.³ These devices use a fine non-cutting polymer or metal tip that is vibrated within the canal space, with different frequencies according to manufacturer's instruction. Sonically activated instruments are driven with a frequency range of 1,000–6,000 Hz and will generate a single node near the point at which the file is attached, as well as an antinode at the tip of the file.⁴⁻⁶ In ultrasonic solutions agitation, a tip oscillates at frequencies of 25 to 30 kHz in a pattern of motion consisting of nodes and anti-nodes along its length.⁷ EndoActivator, a sonically-driven canal irrigation system (Dentsply Tulsa Dental Specialties, Tulsa, OK), has been developed for activating root canal irrigants, and has recently been released onto the market. It comprises a portable hand-piece with three modes (low, medium, and high) and 3 types of disposable flexible non-cutting polymer tips of different sizes. Its design allows for the safe activation of various irrigating solutions and could produce vigorous fluid dynamic in the canal space.⁸ Electrical devices driven sonically has been found to be effective for cleaning root canals in many studies.^{3,9,10} However, for the last decade there has been some conflicting results in the literature on the efficacy of the system and its superiority over other systems. Some researchers have found that sonically activated irrigation is less effective than ultrasonically activated irrigation, while others have suggested that the two methods produce comparable results.^{11,12} To our best knowledge, there have been no previous studies of the physical mechanism through which the electrical sonic driven EndoActivator tip generates bubbles during activation of irrigation solution. In the present study, the mechanism was investigated by acquiring real-time data using a modified extracted tooth and a transparent glass model of root canals in order to visualize the oscillation amplitude of an EndoActivator tip in the solution. Hence, more knowledge of mechanism underlying the activation behavior of the EndoActivator tips in the solutions is crucial to improve the outcomes of the root canal treatment.

MATERIALS AND METHODS

Preparation of a modified extracted tooth

A single-rooted human mandibular first premolar with straight canal and mature apex, and a tooth length of 25 mm was selected. The tooth was not decoronated, and the intact crown (10 mm) acted as a reservoir for the irrigation solution. The preparation of the root canal was completed to the working length (WL) using a Pro Taper hand file (Dentsply Maillefer) up to a size of 25/0.06 as the master apical file (MAF) with the balanced force technique. The distal aspect of the root of the extracted tooth was carefully cut (from cervical to apex) using a fissure diamond bur (Dentsply, Tulsa, OK, USA) until the canal space was exposed (Figure 1a and b), then the surface was ground successively with 240-, P400, and 600-grit sandpaper to give a smooth surface. A glass cover was then carefully glued to the surface without entering the canal, and this was covered with composite (Figure 1c and d). The apex was then sealed with composite and the outer surface of the tooth was covered with nail varnish, ensuring that there were no visible cracks, to allow conditions within the root canal in vivo to be simulated. The tooth was filled with the solution until it reached 5 mm below of the cervical level. The tip of the sonic instrument was inserted 2 mm shorter than the WL. A single modified extracted tooth was used for uniformity in the width and size of the root canal.

Figure 1. (A) A root sample with a longitudinal cut in the distal aspect of the root canal. (B) Exposed root canal space. (C) Exposed tooth with a glass cover (0.15 mm thick). (D) The glass cover glued to the tooth and shaped to fit the shape of the root.

Root Canal Model.

The conditions within a straight root canal were simulated and visualized using a glass model with artificial canal and pulp cavity (which acted as a reservoir). The model was a glass root canal model (Kimia Farma, Bandung, West Java, Indonesia), with canal inner diameter 0.4 mm at the apex, crown height 8 mm, crown diameter 6 mm, a taper of 0.06 and an overall length of 25 mm. The canal was filled with a solution containing 17% EDTA or 3% NaOCl. The apex of the model was sealed with composite to allow the conditions within a root canal to be simulated. Two approaches were used, one

using the air–solution interface (in the coronal portion) and the other using the solution–air interface (in the apical portion). The solution–air interface system represents air entrapment in the apical region (Figure 2). The models were filled with the solution until the level reached 5 mm below the coronal end (air-solution interface system), while in the solution–air interface system, the model was filled with solution starting 5 mm from the apex (air entrapment model). The tip of the sonic instrument was inserted into the solution at the air– solution or solution–air interface (10 mm and 4 mm from the interface, respectively). A single transparent glass model was used for uniformity in the width and size of the root canal.

Figure 2. Illustrations of the solution-air and air-solution systems

Sonic Parameters and Procedure.

A 22 mm polymer noncutting # 25, 0.04 (Dentsply) was mounted on an EndoActivator hand-piece (Dentsply Tulsa Dental Specialties, Tulsa, OK) set at high mode (190 Hz) and used to activate the irrigant. The models were subjected to active sonic irrigation. The tip of the sonic instrument was inserted into the solution at the air–solution (10 mm) or solution–air interface (4 mm), while the tip was inserted 2 mm shorter than the working length in the modified extracted tooth and activated passively without any filing motion. The hand-piece was fixed in a holder to ensure that the desired position was maintained. All the experiments with the different samples were performed by the same operator. (Figures to describe the procedure is needed)

Basic Visualization.

The process was recorded using a Phantom Miro 320S high-speed digital imaging system (Wayne, NJ, USA) at 25,000 frames per second with 320Å~240 pixels per image using a macro lens (60 mm, f/2.8; Nikon, Tokyo, Japan). The root canal model was illuminated using a Fibre-Lite LMI-6000 LED continuous light source (Dolan-Jenner Industries, Boxborough, MA, USA). Measurements were repeated three times for each sample.

RESULTS

Regardless of whether 17% EDTA or 3% NaOCl was used, the high-speed images and

video clearly showed that fluid streaming. The electrical sonic activated EndoActivator tip generated hydrodynamic and finally bubbles formation occurred during the sonic activation process in the solution-air system instead of in the restricted areas (the solution-air system and modified extracted tooth).

Activation in the glass model

Air-solution interface system

During the first 69 μs , the sonic energy was transferred to the tip and the tip vibrated at a frequency of around 190 Hz, causing the solution surface (the air-solution interface) to move as a wave. After 75 μs , macro and micro bubbles formed in the solution. Subsequently, accumulation of the energy during sonic activation at interface caused the micro and macro bubbles in the solution. Finally, the bubbles formation occurred only the vicinity of the tip (Figure 3A). (Supplemental Video S1 <https://youtu.be/ut6VKWDGmj8>). The life cycle of a bubble observed ranges from 250,000–700,000 μs with predominantly 700 μm in diameter. The end of the tip did not generate bubbles formation.

Solution-air interface system

A model with air trapped in the apical region was used, meaning there was a solution column and an air column. The energy of the tip vibration was not sufficiently enough to break the surface tension at the solution-air interface (Figure 3B). (Supplemental Video S2 <https://youtu.be/rqzM0WmJUOY>).

Activation in the modified extracted tooth (air-solution interface system)

No bubbles formation occurred during the activation process (Figure 3C). (Supplemental video S3 <https://youtu.be/-BHdVIO3DkA>).

Figure 3. Representative images showing the disruption of surface tension at the air solution (A) and solution-air systems (B) in glass models, (C) modified extracted human root canal, (D) Oscillation amplitude of EA tip in the air.

DISCUSSION

To be clinically relevant, in vitro studies should reproduce the clinical situation as much

as possible. Human dentin structure is not possible for direct visualization. All the in vitro models were made of transparent glass, and it is noted that glass may behave differently from root-canal-wall material. The results of the in vitro studies may therefore not reflect what actually happens in clinical settings. Avoiding the bias results of in vitro study that it does not mimic the real condition of clinical settings, the authors, in this study, solve this dilemma using modified extracted teeth as model, which more relevant to clinical condition. Comprehensive visualizations were acquired using a high-speed camera and the glass root canal models together with modified teeth, to allow the basic physical mechanism involved in cavitation in the solution during sonic activation to be studied. Ruddle claimed that cavitation **occurs** when a solution is activated using an electrical driven EndoActivator tip.⁸ According to the formula for the cavitation number Ca and the corresponding velocity threshold, which can be calculated using the equation $U = 2\pi fA$, it is not possible for cavitation to occur during an air or electrical sonic activation.^{13,14} It is not clear why bubbles occurred during activation using an **electrical** driven EndoActivator tip in solutions. Cavitation is important to the efficient cleaning of the root canal system.^{15,16} There is a clear need to improve our understanding of the mechanism involved in bubble formation in a solution activated using an electrical driven EndoActivator tip during root canal treatment. Two approaches were used, one using the air–solution interface system (in the coronal portion) and the other using the solution–air interface system (in the apical portion). The solution–air interface system represents air entrapment in the apical region. The process in the air–solution or solution–air systems can be observed closely using the modified extracted tooth and the glass canal model. The high-speed imaging method used enables the capture of images within intervals of **milli**-microseconds. Surprisingly, we clearly observed that the end of the vibrating tip did not generate the formation of bubbles. Furthermore, the tip vibrations disturbed the sonically activated solution interface. The vibrating activator tip transferred its energy to the solution and created waves, and these caused surface waves to form at the interfaces in both systems. In the air–solution interface system, the energy from the vibrating tip (at a certain power setting) was able to change the specific internal energy of the air-solution system to another form of energy.¹⁷ The energy was then transferred to the air-solution interface as pressure waves, disrupting the interface and creating individual surface tension in the form of bubbles. In other words, accumulation of input energy (from the vibrating

tip) was used as kinetic energy for the vibrating tip to generate bubbles. This process set up a series of waves or oscillations at the air-solution interface. Finally, the formation of bubbles then occurred limited to the vicinity of the tip at around 75 μs post-EA tip activation. The life cycle of a bubble observed ranges from 250,000–700,000 μs with predominantly 700 μm in diameter. The authors assumed that the bubbles are not cavitation because it occurred below the threshold needed for cavitation.^{13,14} We have suggested that the vibration pattern of the tip at 190 Hz generated the first mode shape, which has single node and antinode. The node at the attachment and the antinode at the end of the tip, which vibrates freely as a cantilever beam model (back and forth linear movement). A mode shape is defined as a specific pattern of vibration executed by a mechanical system at a specific frequency.¹⁸ The back and forth linear motion of an electrical driven EndoActivator tip generated disruption of surface tension at the air–solution in the form of bubbles in the solution. The process involved the use of air (compressible fluid) and solution (incompressible fluid), which differ in density.¹⁹

The processes in the solution–air interface system showed that the accumulating kinetic energy reaching the surface of the solution (i.e., the solution–air interface) disturbed the surface and produced surface waves. However, the surface tension was just adequate to generate waves and acoustic streaming but not cavitation. We conclude that the energy transferred from the activator tip to the solution was not sufficient to disrupt the surface tension at interface. Surface tension is defined as the attractive force between molecules (internal energy) acting to decrease the surface area of a liquid. This produces a layer of surface molecules on the liquid that acts like a stretched membrane.²⁰ In particular, this internal energy limits the flow of the liquid into narrow canals. It suggests that the surface tension internal energy of the solution, acting at the solution-air interface, has an important role in preventing bubbles generation.²⁰ Furthermore, in restricted areas, due to the oscillation amplitude of the EA tip to be 5 mm (Figure 3D), the sonic driven tip will undergo much more wall contact, which inhibits the tip vibration and may reduce the efficient streaming of the irrigant. This phenomenon occurred in the restricted areas such as modified extracted tooth.¹¹ Although each image was captured in a different root canal model, the dynamics of pressure waves, bubble formation, and wave formation proved to be reproducible in this in vitro study.

To the best of our knowledge, this method of visualizing fluid dynamics and bubbles formation in real-time using real human tooth structures has not been used in any previous study. We believe that the results of this study improve our initial understanding of the basic mechanisms involved in the fluid dynamics in a solution used to treat root canals by means of an electrical driven EndoActivator tip. Further studies are required to investigate the natural frequencies of tip to improve its efficacy.

CONCLUSIONS

Regardless of the solution type, our results show that fluid streaming and bubbles formation occur in a solution when activated by an electrical driven EndoActivator tip at the air-solution interface, instead of at the solution-air interface and modified extracted tooth.

ACKNOWLEDGMENTS

The authors deny any conflict of interest related to this study. The authors would like to thank Professor Zainal Abidin PhD at the Institut Teknologi Bandung (Bandung, Indonesia), and Mr. Wowo Watumas at the Phantom Company for their helpful contributions to discussions.

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Figure 1

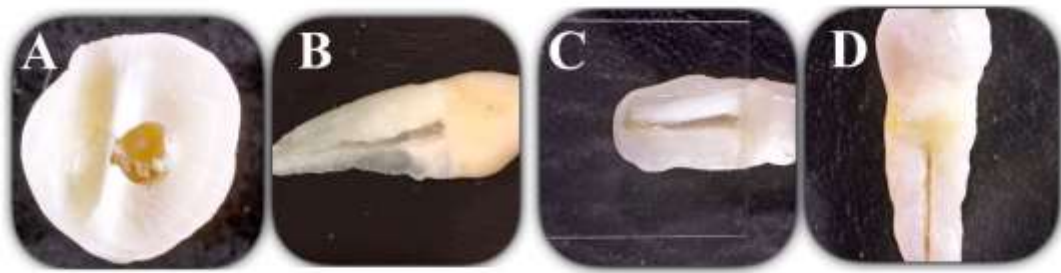


Figure 2

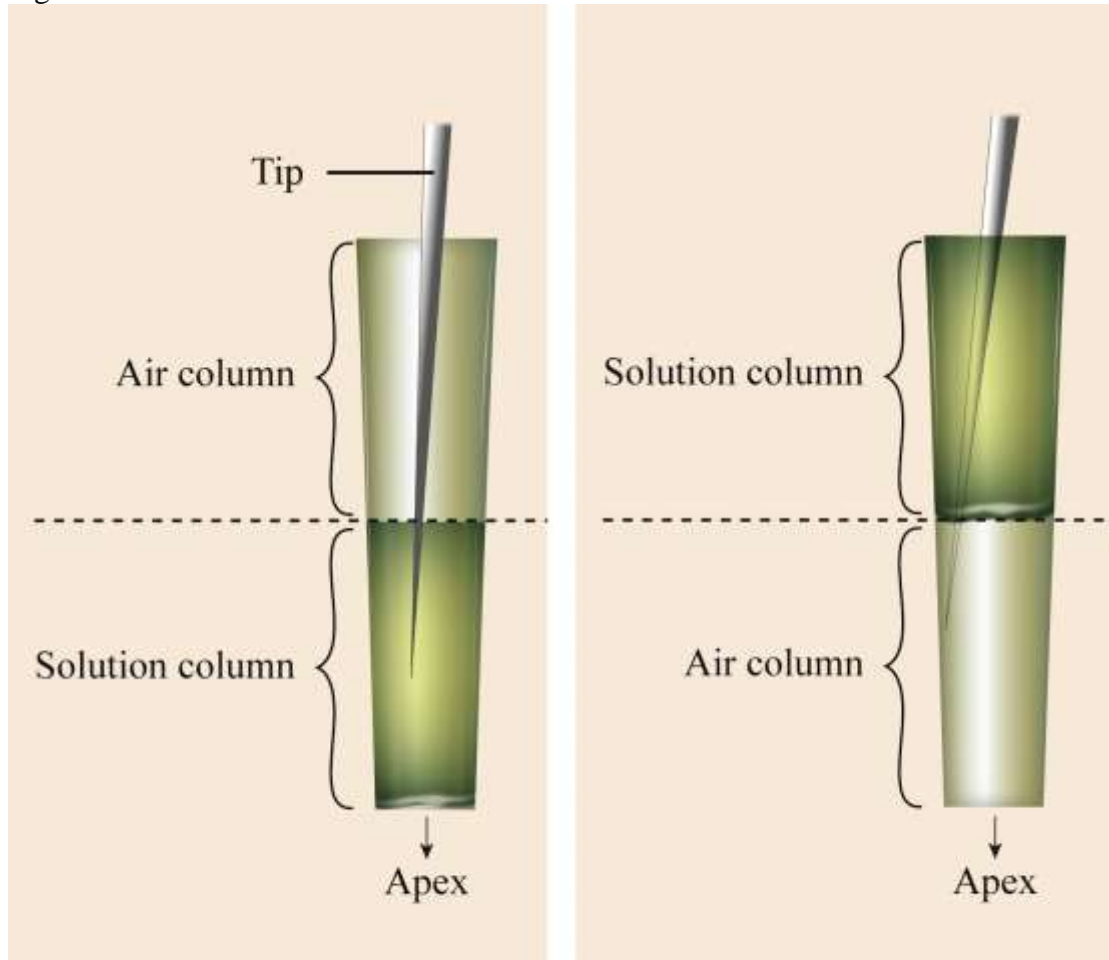
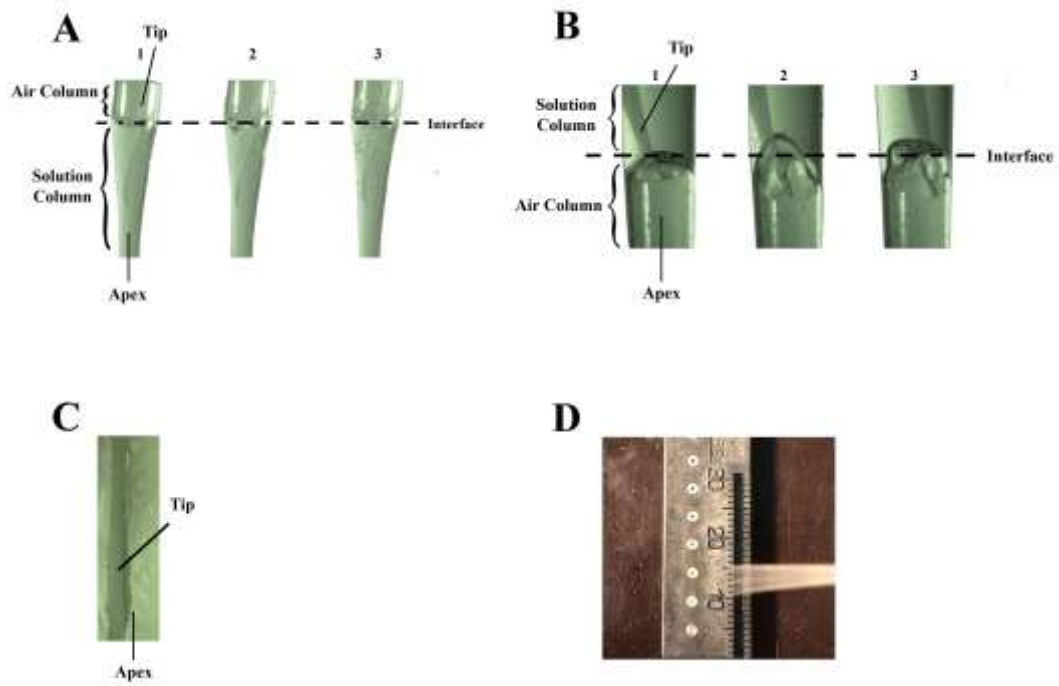


Figure 3



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4. In the discussion, regarding the preparation of natural tooth with Balanced Force technique using Protaper hand file, what is your reasoning of using this technique and file? From the photo of the natural tooth, the root canal anatomy is somewhat not straight, why do you choose non straight canal? Please add your reasons in the discussion.
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Visualization of bubbles generation of electrical-driven EndoActivator tips during solutions activation in a root canal model and a modified extracted tooth: A pilot study

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ABSTRACT

Background: *EndoActivator*, a sonically-driven canal irrigation system (Dentsply Tulsa Dental Specialties, Tulsa, OK), has been developed for activating root canal irrigants, and has recently been released onto the market. **Purpose:** To obtain an initial understanding of bubbles generation of electrical *EndoActivator* tips during activation of the irrigant in a transparent root canal model and a modified extracted tooth. **Methods:** A modified extracted tooth and a straight glass model were filled with a solution containing 17% EDTA or 3% NaOCl. A medium activator tip 22-mm polymer noncutting #25, 0.04 file driven by an electrical sonic hand-piece at 190 Hz (highest level) induced pressure waves that produced macro- and micro-bubbles. The physical mechanisms involved were visualized using a Miro 320S high-speed imaging system (Phantom, Wayne, NJ, USA) with high temporal and spatial resolutions. The imaging system acquired images at 25,000 frames per second with 320x240 pixels per image, and attached a 60-mm f/2.8 macro lens (Nikon, Tokyo, Japan). **Results:** The end of the tip did not generate bubbles formation. Disruption of surface tension at the air–solution system in the glass canal model by an electrical sonic driven *EndoActivator* tip generated bubbles in the solution. However, it did not occur at the system of solution–air interfaces in the glass canal and modified extracted tooth. **Conclusion:** The physical mechanism of the solution activated by an electrical sonic driven *EndoActivator* tip in generating bubbles formation is because the surface tension at the air–solution system disruption. No bubbles formation occurred in the solution in the restricted space either in the solution-air system or modified extracted tooth. Better understanding of the physical mechanisms that relate specifically to the activation behaviour of *EndoActivator* tips in solutions is key to improving the cleaning mechanism that applies during root canal treatment.

Keywords: bubbles formation; *EndoActivator*; endodontics; sonic

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INTRODUCTION

Non-automated agitation of the irrigant can be produced using a file or a guttapercha cone that is inserted in the shaped and cleaned canal and subsequently moved periodically and rapidly by the operator.^{1,2} Electrical ultrasonic and sonic devices are examples of automated agitation.³ These devices use a fine non-cutting polymer or metal tip that is vibrated within the canal space, with different frequencies according to manufacturer's instruction. Sonically activated instruments are driven with

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MATERIALS AND METHODS

A single-rooted human mandibular first premolar with straight canal and mature apex, and a tooth length of 25 mm was selected. The tooth was not decoronated, and the intact crown (10 mm) acted as a reservoir for the irrigation solution. The preparation of the root canal was completed to the working length (WL) using a Pro Taper hand file (Dentsply Maillefer) up to a size of 25/0.06 as the master apical file (MAF) with the balanced force technique. The distal aspect of the root of the extracted tooth was carefully cut (from cervical to apex) using a fissure diamond bur (Dentsply, Tulsa, OK, USA) until the canal space was exposed (Figure 1A and B), then the surface was ground successively with 240-, P400, and 600-grit sandpaper to provide a smooth surface. A glass cover was then carefully glued to the surface without entering the canal, and this was covered with composite (Figure 1C and D). The apex was then sealed with composite resin and the outer surface of

the tooth was covered with nail varnish, ensuring that there were no visible cracks, to simulate conditions within the root canal *in vivo*. The tooth was filled with the solution until it reached 5 mm below of the cervical level. The tip of the sonic instrument was inserted 2 mm shorter than the WL. A single modified extracted tooth was used for uniformity in the width and size of the root canal.

The conditions within a straight root canal were simulated and visualized using a glass model with artificial canal and pulp cavity (which acted as a reservoir). The model was a glass root canal model (Kimia Farma, Bandung, West Java, Indonesia), with canal inner diameter was 0.4 mm at the apex, crown height was 8 mm, crown diameter was 6 mm, a taper of 0.06 and an overall length of 25 mm. The canal was filled with a solution containing 17% EDTA or 3% NaOCl. The apex of the model was sealed with composite to allow the conditions within a root canal to be simulated. Two approaches were used, one used the air–solution interface (in the coronal portion) and the other used the solution–air interface (in the apical portion). The solution–air interface system represents air entrapment in the apical region (Figure 2). The models were filled with the solution until the level reached 5 mm below the coronal end (air–solution interface system), while in the solution–air interface system, the model was filled with solution starting 5 mm from the apex (air entrapment model). The tip of the sonic instrument was inserted into the solution at the air– solution or solution–air interface (10 mm and 4 mm from the interface, respectively). A single transparent glass model was used for uniformity in the width and size of the root canal.

A 22-mm polymer noncutting # 25, 0.04 file (Dentsply) was mounted on an EndoActivator hand-piece (Dentsply Tulsa Dental Specialties, Tulsa, OK) set at high mode (190 Hz) and used to activate the irrigant. The models were subjected to active sonic irrigation. The tip of the sonic instrument was inserted into the solution at the air–solution (10 mm) or solution–air interface (4 mm), while the tip was inserted 2 mm shorter than the working length in the modified extracted tooth and activated passively without any filing motion. The hand-piece was fixed in a holder to ensure that the desired position was maintained. All the experiments with the different samples were performed by the same operator.

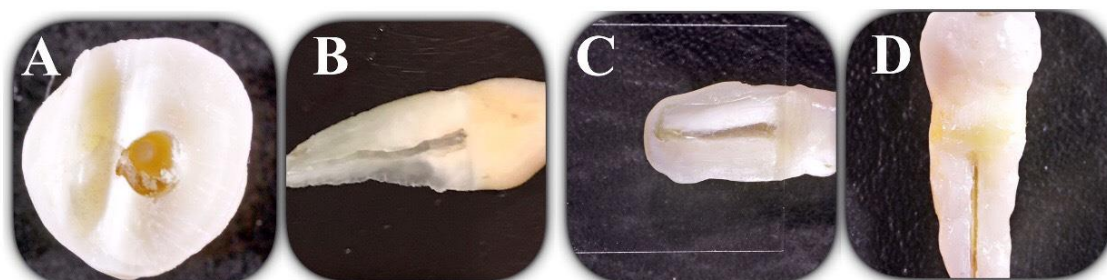


Figure 1. (A) A root sample with a longitudinal cut in the distal aspect of the root canal. (B) Exposed root canal space. (C) Exposed tooth with a glass cover (0.15 mm thick). (D) The glass cover was glued to the tooth and shaped to fit the shape of the root.

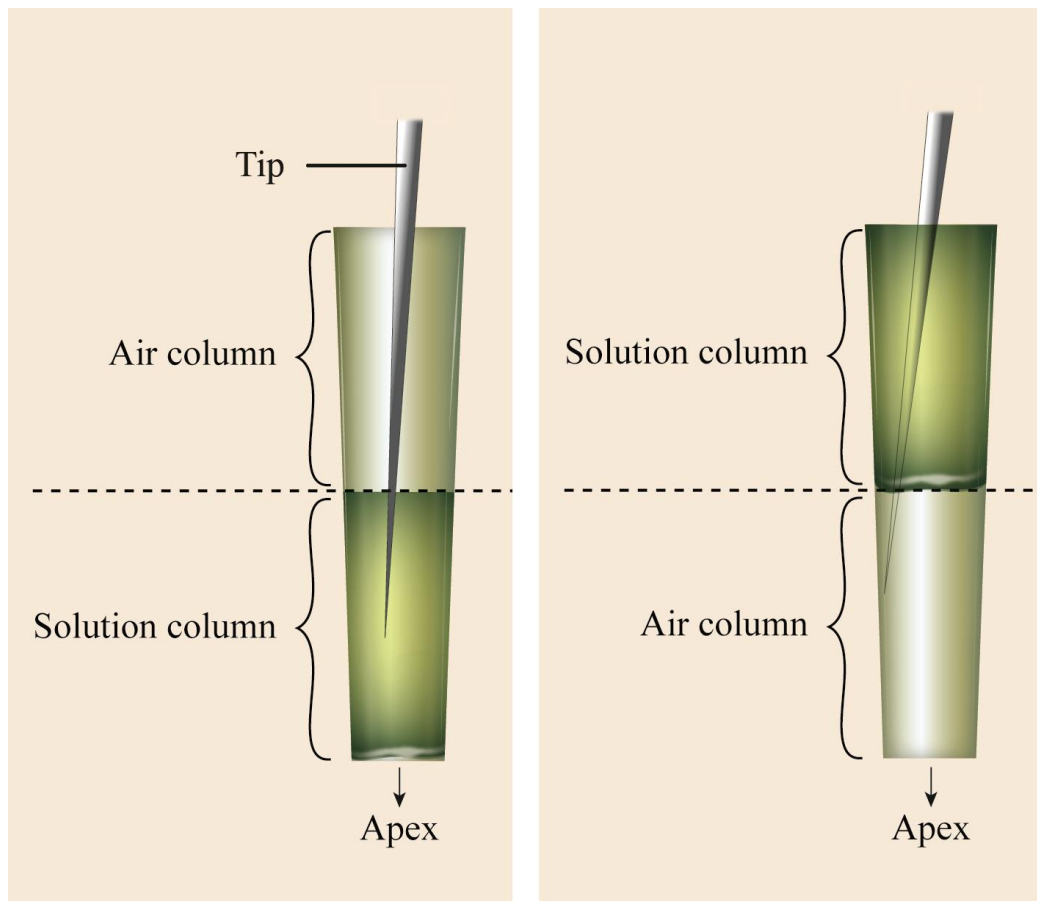


Figure 2. Illustrations of the solution-air and air-solution systems.

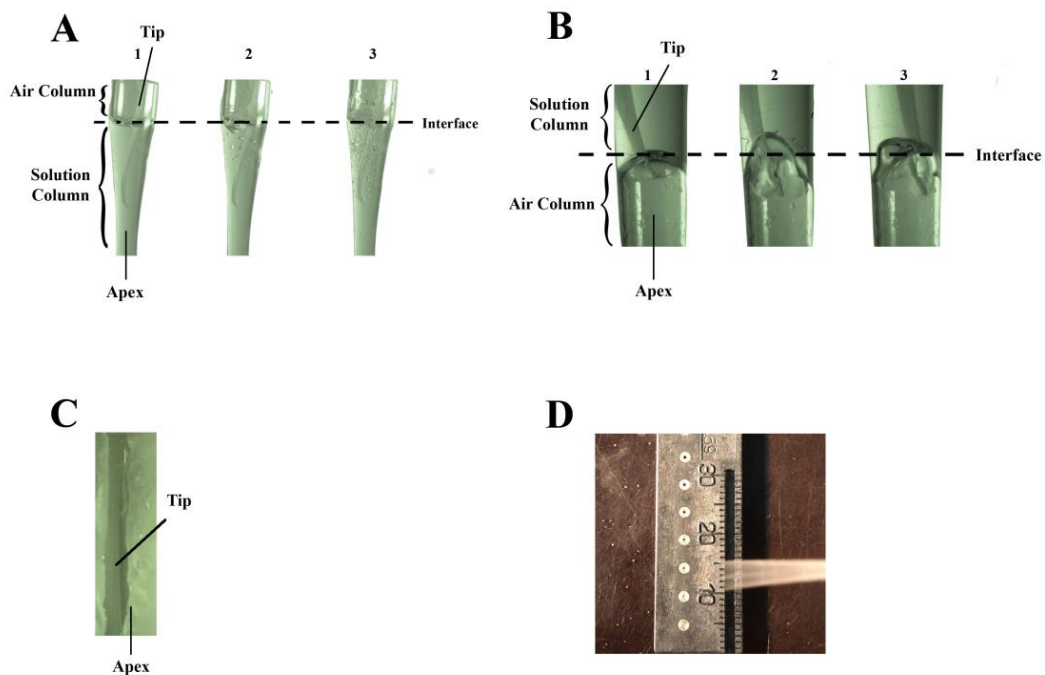


Figure 3. Representative images showing the disruption of surface tension at the air solution (A) and solution-air systems (B) in glass models, (C) modified extracted human root canal, (D) Oscillation amplitude of the EA tip in the air.

The process was recorded using a Phantom Miro 320S high-speed digital imaging system (Wayne, NJ, USA) at 25,000 frames per second with 320x240 pixels per image using a macro lens (60 mm, f/2.8; Nikon, Tokyo, Japan). The root canal model was illuminated using a Fibre-Lite LMI-6000 LED continuous light source (Dolan-Jenner Industries, Boxborough, MA, USA). Measurements were repeated three times for each sample.

RESULTS

Regardless of whether 17% EDTA or 3% NaOCl was used, the high-speed images and video clearly showed fluid streaming. The electrical sonic activated EndoActivator tip generated hydrodynamic and finally bubbles formation occurred during the sonic activation process in the solution-air system instead of in the restricted areas (the solution-air system and modified extracted tooth). Oscillation amplitude of the EA tip in the air was approximately 5 mm.

During the first 69 μ s, the sonic energy was transferred to the tip and the tip vibrated at a frequency of approximately 190 Hz, causing the solution surface (the air-solution interface) to move as a wave. After 75 μ s, macro and micro bubbles formed in the solution. Subsequently, accumulation of the energy during sonic activation at interface caused the micro and macro bubbles in the solution. Finally, the bubbles formation occurred only the vicinity of the tip (Figure 3A). (See supplemental video S1 at <https://youtu.be/ut6VKWDGmj8>). The life cycle of a bubble observed ranges from 250,000–700,000 μ s with predominantly 700 μ m in diameter. The end of the tip did not generate bubbles formation.

A model with air trapped in the apical region was used; thus, there was a solution column and an air column. The energy of the tip vibration was not sufficiently enough to break the surface tension at the solution-air interface (Figure 3B). (See supplemental video S2 at <https://youtu.be/rqzM0WmJUOY>). No bubbles formation occurred during the activation process in the modified extracted tooth (air-solution interface system) (Figure 3C). (See supplement video S3 <https://youtu.be/-BHdVIO3DkA>).

DISCUSSION

To be clinically relevant, *in vitro* studies should reproduce the clinical situation as much as possible. Human dentin structure is not possible for direct visualization. All the *in vitro* models were made of transparent glass, and it is noted that glass may behave differently from root-canal-wall material. The results of the *in vitro* studies may therefore not reflect what actually occurs in clinical settings. Avoiding the bias results of *in vitro* study that it does not mimic the real condition of clinical settings, the authors, in this study, solve this dilemma using modified extracted teeth as models, which more relevant to clinical

condition. Comprehensive visualizations were acquired using a high-speed camera and the glass root canal models together with modified teeth, to allow the basic physical mechanism involved in bubbles formation in the solution during sonic activation to be studied. Ruddle⁸ claimed that cavitation occur when a solution is activated using an electrical-driven EndoActivator tip. According to the formula for the cavitation number Ca and the corresponding velocity threshold is 15 m/sec, the velocity of the file which can be calculated using the equation $U = 2\pi fA$ (with f being the file oscillation frequency and A is the amplitude of oscillation). The EA tip oscillating at a frequency of 190 Hz and oscillation amplitude of 5 mm oscillates with a velocity of 5.9 m/sec, it is not possible for cavitation to occur during an air or electrical sonic activation.^{13,14} It is not clear why bubbles occurred during activation using an electrical-driven EndoActivator tip in solutions. Cavitation is important to the efficient cleaning of the root canal system.^{15,16} There is a clear need to improve our understanding of the mechanism involved in bubble formation in a solution activated using an electrical-driven EndoActivator tip during root canal treatment. Two approaches were used, one using the air-solution interface system (in the coronal portion) and the other using the solution-air interface system (in the apical portion). The solution-air interface system represents air entrapment in the apical region. The process in the air-solution or solution-air systems can be observed closely using the modified extracted tooth and the glass canal model. The high-speed imaging method used enables the capture of images within intervals of mili-microseconds. Surprisingly, we clearly observed that the end of the vibrating tip did not generate the formation of bubbles. Furthermore, the tip vibrations disturbed the sonically activated solution interface. The vibrating activator tip transferred its energy to the solution and created waves, and these caused surface waves to form at the interfaces in both systems.

In the air-solution interface system, the energy from the vibrating tip (at a certain power setting) was able to change the specific internal energy of the air-solution system to another form of energy.¹⁷ The energy was then transferred to the air-solution interface as pressure waves, disrupting the interface and creating individual surface tension in the form of bubbles. In other words, accumulation of input energy (from the vibrating tip) was used as kinetic energy for the vibrating tip to generate bubbles. This process created a series of waves or oscillations at the air-solution interface. Finally, the formation of bubbles then occurred limited to the vicinity of the tip at around 75 μ s post-EA tip activation. The life cycle of a bubble observed ranges from 250,000–700,000 μ s with predominantly 700 μ m in diameter. The authors have suggested that the bubbles are not cavitation because it occurred below the threshold needed for cavitation.^{13,14} The experiment showed that the vibration pattern of the tip at 190 Hz generated the first mode shape, which has single node and an antinode. The node at the attachment and the antinode at the end of the

tip, which vibrates freely as a cantilever beam model (back and forth linear movement). A mode shape is defined as a specific pattern of vibration executed by a mechanical system at a specific frequency.¹⁸ The back and forth linear motion/pendulum of an electrical-driven EndoActivator tip generated disruption of surface tension at the air–solution in the form of bubbles in the solution. The process involved the use of air (compressible fluid) and solution (incompressible fluid), which differ in density.¹⁹

The processes in the solution–air interface system showed that the accumulating kinetic energy reaching the surface of the solution (i.e., the solution–air interface) disturbed the surface and produced surface waves. However, the surface tension was just adequate to generate waves and streaming but not cavitation. We conclude that the energy transferred from the activator tip to the solution was not sufficient to disrupt the surface tension at the interface. Surface tension is defined as the attractive force between molecules (internal energy) acting to decrease the surface area of a liquid. This produces a layer of surface molecules on the liquid that acts like a stretched membrane.²⁰ In particular, this internal energy limits the flow of the liquid into narrow canals. It suggests that the surface tension internal energy of the solution, acting at the solution–air interface, has an important role in preventing bubbles generation.²⁰ Furthermore, in restricted areas, due to the oscillation amplitude of the EA tip to be 5 mm (Figure 3D), the sonic driven tip will make more wall contact, which inhibits the tip vibration and may reduce the efficient streaming of the irrigant. This phenomenon occurred in the restricted areas such as modified extracted tooth.¹¹ Although each image was captured in a different root canal model, the dynamics of pressure waves, bubble formation, and wave formation proved to be reproducible in this *in vitro* study.

To the best of our knowledge, this method of visualizing fluid dynamics and bubbles formation in real-time using real human tooth structures has not been used in any previous study. We believe that the results of this study improve our initial understanding of the basic mechanisms involved in the fluid dynamics in a solution used to treat root canals by means of an electrical-driven EndoActivator tip. Further studies are required to investigate the natural frequencies of the tip to improve its efficacy. Regardless of the solution type, our results show that fluid streaming and bubbles formation occurred in a solution when activated by an electrical-driven EndoActivator tip at the air–solution interface, instead of at the solution–air interface and modified extracted tooth.

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