EFFECTS OF IRRIGATION AND AGITATION ON APICAL VAPOR LOCK
an *ex-vivo* study

by
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The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, the thesis entitled:

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Abstract

Objectives: 1- To detect the presence of apical vapor lock after positive pressure irrigation at two needle insertion depths. 2- To evaluate the elimination of apical vapor lock by manual dynamic agitation. 3- To investigate the replacement of the contrast solution with sodium hypochlorite at two needle insertion depths and flow rates.

Methodology: Twenty-eight single rooted teeth were shaped with either Vortex Blue 25/04 or ProTaper Gold F2 (25/08) rotary files. Presence of apical vapor lock was detected radiographically using a contrast mixture (sodium hypochlorite & cesium chloride) as the irrigant. Manual dynamic agitation with 50 strokes of a well fitting gutta percha cone was performed in teeth with apical vapor lock. Its elimination was then evaluated radiographically. In teeth in which apical vapor lock was eliminated, replacement of the contrast solution with sodium hypochlorite was assessed radiographically. Each tooth was then shaped with Vortex Blue 30/04 or ProTaper Gold F3 (30/09) rotary files and the aforementioned experiments were repeated.

Results: Apical vapor lock was detected in 92.0% of the samples. Manual dynamic agitation eliminated the apical vapor lock in 81.6% of the teeth. Apical vapor lock was more likely to be present and eliminated in teeth that were shaped with ProTaper Gold rotary files. Increase in the flow rate, increase in the needle insertion depth, shaping with Vortex Blue rotary files and smaller apical preparation size improved the replacement of the contrast solution.

Conclusion: Within the limitations of this study, shaping with ProTaper Gold rotary files has a joint effect in the formation and elimination of apical vapor lock. Replacement of the contrast solution with sodium hypochlorite was affected by the independent effects of needle insertion depth and flow rate and the joint effect of needle insertion depth, flow rate, rotary file system and apical size preparation.

Lay Summary

A canal system may have a complex anatomy with areas where no instruments can reach. Therefore, irrigation with solutions such as sodium hypochlorite may reach those areas and better clean and disinfect the canal system. Clinically, a tooth is enclosed in the bone forming a closed end system. Air can get entrapped when irrigant is introduced into a dry canal with a closed end. This air entrapment is called apical vapor lock and can adversely impact the cleaning and disinfection of the canal system. Presence of apical vapor lock may be visualized radiographically by adding a contrast agent to an irrigant before it is introduced into a canal with closed end. The apical vapor lock may be eliminated by manual dynamic agitation, repeated strokes of a well fitting gutta. When apical vapor lock is eliminated, irrigant may reach the full length of the canal system successfully.

Preface

This study was approved by the University of British Columbia Clinical research Ethics Board (Certificate H12-02430).

The relative contribution of the collaborators in this project was:

Dr. Parisa Farmand (70%) : Identification and design of the research project, Performance of the various parts of the research, Collection and analysis of the research data, Writing of the dissertation

Dr. Markus Haapasalo (15%) : Design of the research project, Analysis of the research data, Editing of the dissertation

Dr. Jolanta Aleksejuniene (10%) : Statistical analysis, Editing of the dissertation

Dr. Ya Shen (5%) : Editing of the dissertation

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List of Abbreviation

AVL	Apical vapor lock
BL	Bucco-lingual
CBCT	Cone beam computed tomography
CsCl	Cesium chloride
CFD	Computational fluid dynamics
ISO	International Organization for Standardization
MD	Mesio-distal
NaOCl	Sodium hypochlorite
PPI	Positive pressure irrigation
PTG	ProTaper Gold
SEM	Scanning electron microscopy
VB	Vortex Blue
WL	Working length
WL-1	1.0 mm short of working length
WL-2	2.0 mm short of working length
WL-3	3.0 mm short of working length

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Dedication

This dedication is for my beloved parents who selflessly gave all for my better future and still do unconditionally. It is for my grandmother who endlessly encouraged all her children and grand-children to serve people, the ones in need and the ones in pain and lastly for my partner in life who is always there for me from far distance.

Chapter 1: Literature Review

1.1 *The main goal in endodontics*

The main goal in endodontics is to treat apical periodontitis and to prevent its occurrence in future (Ørstavik & Pitt Ford, 2008; Siqueira et al., 2014). Apical periodontitis is the destruction of the peri-radicular tissue by the host inflammatory responses to the microbial challenge of endodontic origin (Nair et al., 2005). In 1965, Kakehashi et al. established the knowledge that microorganisms are required for the emergence of periapical disease as no apical periodontitis developed in germ free rats whose molar pulps were exposed to oral cavity compared to the rats with normal oral microflora (Kakehashi et al., 1965). Soon after, obligate anaerobic bacteria were found to play a great role in endodontic infections (Moller, 1966). Later on, it was shown that an endodontic infection comprises a mixture of several species of which strict anaerobes are the dominant species (Sundqvist, 1976). Due to complex mixture of disease causing bacterial species and complex anatomy of the root canal system, sterilization may be highly improbable (Siqueira & Rôças, 2008). Hence, in order to treat apical periodontitis, endodontics aim to reduce the bacterial population density (load) in the root canal system to below what is required to induce and sustain periapical disease (Siqueira & Rôças, 2008). To attain a lower bacterial load, a successful root canal treatment relies on the effectiveness of chemomechanical preparation that combines the benefits of chemical and mechanical processes to debride the root canal system.

1.2 *The chemomechanical preparation*

Chemomechanical preparation relies on the mechanical debridement by instrumentation, mechanical flushing by irrigation and chemical removal of vital, necrotic tissue, microorganisms and their toxins by the irrigants' antibacterial and tissue dissolving properties (Gulabivala et al., 2005). Such debridement and disinfection mainly targets the main root canal, the most voluminous part of the canal system. However, studies on root canal morphology have shown the complex anatomy of the root canal system that varies from one tooth to another. This complexity includes irregularities, lateral canals, apical deltas, fins, webs and transverse anastomoses (Vertucci, 1984). This complex design has even rendered the modern techniques incapable of sterilizing the root canal system and has limited the effect of thorough chemomechanical preparation (Gulabivala et al., 2005). Mechanical instruments are either hand or engine driven. The advancements in the instrument design expedited with the introduction of nickel titanium in 1988 (Walia & Brantley, 1988). Nickel titanium's super-elastic nature has allowed researchers to continuously modify the design of the instruments, with the purpose of improving canal debridement, and also to increase fracture resistance and safety in the hands of clinicians. Many studies have been conducted to compare the efficacy of different rotary file systems in canal debridement and as new systems develop, more studies will be conducted. Mechanical instrumentation substantially reduces the bacterial load but does not render the canal free of tissue and bacteria (Dalton et al., 1998). This is because mechanical instrumentation can potentially leave portions of the root canal system untouched. For instance, an *ex-vivo* experiment has shown that mechanical instrumentation with ProTaper Gold leaves 65.2%-74.4% of the apical 4mm of the oval shaped canals in the distal roots of mandibular molars untreated (Paqué et al., 2010). Research is continuously advancing to design instruments, such as self-adjusting files, that can adapt to the canal walls better and deliver irrigant simultaneously for a better cleaning

(Metzger et al., 2010). However, no rotary file system has been proven, with confidence, to address all the hides and irregularities of the canal system. Such shortcomings of mechanical instrumentation have emphasized on the importance of irrigation to reach areas where the metal instruments cannot plane.

1.3 *Importance of irrigation*

Irrigation is a very important component of chemomechanical preparation. It complements instrumentation by reaching further into areas where no hand or engine driven files can reach. The history of using irrigation in endodontics is dated back to the 19th century when pulp was removed using heat cautery and use of explosive mixtures of sodium and potassium (Sedgley, 2004). Syringing of root canals with hydrogen peroxide became the common irrigation method in the early 20th century (Sedgley, 2004). Sodium hypochlorite (NaOCl, 0.5%) was first used by Henry Drysdale Dakin to treat the wounds of the soldiers during World War I (Sedgley, 2004). In the field of endodontics, NaOCl has been the common irrigant with superior tissue dissolving capacity as compared to other endodontic irrigants such as chlorhexidine, 30.0 % hydrogen peroxide and 10.0% citric acid (Naenni et al., 2004). NaOCl has also superior antibacterial efficacy on bacteria in planktonic (Marshall & Rosen, 1970) and biofilm states (Stojicic et al., 2011). In a clinical experiment, it was shown that mechanical instrumentation with saline reduced the bacterial cells from 10^4- 10^6 to 10^2 - 10^3 and that bacteria were not detected in 7 out of 15 experimental teeth. When 0.5% NaOCl was used as the irrigant instead of the saline during instrumentation, no bacteria could be detected in 12 out of 15 of teeth after 5 appointments (Byström & Sundqvist, 1983). In many of the historical studies on bacterial reduction, samples were collected on paper points that were inserted in the canals. Thus, the bacteria hiding in accessory canals, fins, webs and isthmi could go undetected by this technique. Some other studies have used light microscopy to examine the efficacy of irrigation. For instance, a clinical study on surgically removed apical portions of teeth after root canal treatment showed existence of residual bacteria biofilm in the recesses in 14 out of 16 specimens which questioned the efficacy of NaOCl in chemomechanical preparation (Nair et al., 2005). Another study showed presence of remaining pulp tissue in the apical 1.0 mm and the isthmi of the mesial root of mandibular molar after mechanical instrumentation and introduction of sodium hypochlorite for 15 and 30 minutes (Senia et al., 1971). According to the researchers, factors such as surface contact, volume of irrigation, limited exchange of solution in the deeper part of the root canal system and use of larger needles that limited the insertion depth into the root canal could have contributed to the poor efficacy of NaOCl (Senia et al., 1971). Also in one *ex-vivo* experiment, it was shown that better canal debridement is due to the mechanical flushing by larger volume of irrigant and that saline, sodium hypochlorite and hydrogen peroxide show similar effectiveness in canal debridement. Hence the authors concluded that it was the mechanical flushing by larger volume of irrigant that was more important than the type of the solution used as the irrigant (Baker et al., 1975). It has been shown, in another *ex-vivo* study, that lack of irrigation during the mechanical instrumentation can cause more than 75.0% debris collection in a canal compared to when irrigation is used (Baker et al., 1975). The formed debris can contain bacteria that can be potentially pushed into the isthmi and other irregularities of the canal system. This complicates and even makes it impossible for the bacteria and remaining tissue to be completely eliminated, especially in the apical portion of the root canal, by the modern techniques of irrigation and instrumentation (Paqué et al., 2010). These occluded places also do not allow entry of the sealer and root canal filling materials for the potential elimination of the bacteria (Endal et al., 2011).

1.4 *A review of irrigation studies*

The shortcomings of irrigation in reaching the apical third as well as the hides and irregularities of the root canal system are attributed to multitude of factors: apical size instrumentation, canal length, irrigant volume, and needle insertion depth (Usman et al., 2004). In a clinical study, Salzgeber and Brilliant (1977) visualized the penetration of a radiography contrast agent after complete chemomechanical preparation. The authors concluded that an apical preparation of an at least ISO size 30 is needed for the irrigant to reach the apical part of the root canal system (Salzgeber & Bril-liant, 1977). One historical study also showed that when needle is placed in the coronal third of the canal system, an apical preparation of at least ISO size 40 and ideally ISO size 60 is required for the effective irrigation and replacement of radiopaque solution in the apical third of the canal (Ram, 1977). In another study, Abou-Rass and Piccinino (1982) demonstrated the need for placement of needle in the apical third of the canal for the effective irrigation delivery. In that *ex-vivo* experiment, the authors used an open-ended 30-gauge needle to irrigate the canal with an anesthetic solution which was mixed with a contrast agent and dentin shaving for radiographic visualization of the irrigant penetration into the canal system (Abou-Rass & Piccinino, 1982). The importance of needle insertion depth was also shown in an *in-vitro* model, a glass root canal with small stained particle beads 10 – 40 µm in size (Chow, 1983). That study along with other studies showed that there is limited flushing effectiveness beyond the needle tip (Kahn et al., 1995; Druttman & Stock, 1989). The contemporary irrigation studies have used thermal imaging analysis, computational fluid dynamics and stained collagen film to better assess the flow pattern of irrigants in a confined canal system. In an *ex-vivo* study in extracted teeth, thermal imaging analysis showed that when a 27-gauge needle is placed at WL-3 in a canal shaped to ISO size 30, successful irrigation was achieved. However, an ISO size 50 was required for the effective irrigation if the needle was to be placed at WL-6 (Hsieh et al., 2007). Use of stained collagen bio-molecular film to represent the biofilm has been another model to study the effectiveness of irrigation. One study used such model and quantified the canal surfaces that were covered with stained collagen before and after irrigation and also examined the efficacy of manual dynamic agitation (MDA) with a well matching gutta percha cone. The authors concluded that depth of needle placement, apical size, taper of the canal preparation and use of dynamic irrigation were the factors (in order of decreasing priority) contributing to an effective irrigation and hence the removal of collagen film (Huang et al., 2008). Computational fluid dynamics (CFD) is the application of both engineering and physical sciences in endodontics to study irrigation and its flow pattern (Gulabivala et al., 2010). Use of such mathematical model has led to standardization between experiments and enhanced the current knowledge of the probable fluid dynamics and behavior in a root canal system. Using the CFD, the stagnation plane, the extent of irrigation from the needle tip, has been shown to be 2.3 mm beyond which is the " dead zone" (Gao et al., 2009). Therefore, the larger/further the stagnation plane, the better the penetration of irrigation. Furthermore, the design of irrigation needle influences the stagnation plane. Notched or slotted needle results in 3.0 mm of cleared zone/stagnation plane whereas a close-ended side vented needle causes less irrigation penetration and hence smaller stagnation plane (Shen et al., 2010). In another study using the CFD modeling, full length penetration of the irrigant was possible when close-ended side vented needle was placed at WL-1 whereas open-ended flat needle could be placed farther at WL-2 (Boutsioukis et al., 2010). At clinically relevant flow rates 0.01 ml/s-0.260 ml/s (0.60 ml/min- 15.60 ml/min), the irrigant penetration extends to only 1.0 mm beyond the needle tip whereas at much higher clinically irrelevant flow rates 0.53 ml/s-0.79 ml/s (31.80 ml/min-47.40 ml/min), the stagnation plane extends to 1.5 mm beyond the needle tip

(Boutsioukis et al., 2009). The aforementioned studies confirm the limited irrigation penetration beyond the needle tip during conventional syringe delivery. Moreover, it is known that laminar flow during conventional syringe delivery cannot exert the shear forces needed to mechanically remove debris and bacterial biofilm from the canal walls (Gulabivala et al., 2010). Fluid flow can be either laminar or turbulent. Reynolds number, ratio of inertial forces to viscous forces, determines the type of the fluid flow. Low Reynolds number indicates the dominance of viscous forces and therefore the resultant laminar flow whereas high Reynolds number indicates dominance of inertial forces and therefore the resultant turbulent flow. A root canal presents a system with a low Reynolds number where fluid flow is laminar. This type of flow is characterized by the slow movement of fluid against the canal walls (Gulabivala et al., 2010) that cannot cause mechanical flushing of debris and bacterial from the canal walls. Prior to evaluating possible means to improve penetration of an irrigant and its flow pattern, it is imperative to discuss the concept of "apical vapor lock" in the following subsection.

1.5 *Apical vapor lock*

Under clinical situations, a tooth is enclosed and supported by the periodontium. The apical foramen and other portals of exit in a root canal system are not open to an easy exchange of air and fluid with the external environment although periapical lesions, perforations, oro-antral communications can create pathways of reduced resistance (Boutsioukis et al., 2013). The root canal system can be considered as a closed-end channel that can entrap air and produce a vapor lock during irrigation (Pesse et al., 2010). The entrapped air or the " apical vapor lock" (AVL) has been hypothesized to form from different resources: by advancing front of the irrigant during its delivery into a dry root canal system (Gu et al., 2009) and by coalescence of gas bubbles (ammonia & carbon dioxide) that are formed as the result of reaction between NaOCl and organic tissue in the canal (Gu et al., 2009). Recently, numerous studies have attempted to address the influential effect of AVL on irrigation penetration (Tay et al., 2010; Susin, et al., 2010; Parente et al., 2010). The first *ex-vivo* experiment to compare the debris and smear removal in closed and open system models was conducted by Tay et al. (2010). The closed system was designed by the application of hot glue over the root apex. The chemomechanical preparation of the experimental teeth were performed by shaping to size 50/04 and syringe delivery of 1.3% NaOCl using a 30-gauge close-ended side vented needle placed at WL-1 followed by syringe delivery of Biopure MTAD that stayed in the canal for 5 minutes. After the final cleaning and shaping, SEM and light microscopy analyses were performed to assess debris and smear removal in each system. Also AVL in a few experimental teeth was visualized radiographically by introducing cesium chloride, CsCl (a contrast agent), into the root canal system using a 30-gauge close-ended side vented needle at WL-1. The results indicated significantly more debris in the apical, middle and coronal parts of the canal systems with closed ends when compared to those in teeth with open ends. Moreover using the contrast agent, the authors were able to visualize the AVL as a radiolucent space in the apical 0-2.0 mm of teeth with closed system design whereas there was no AVL in the teeth with open system design and CsCl fully penetrated the full length of the canals (Tay et al., 2010). That study highlights the importance of a closed system design as another *ex-vivo* experiment has shown complete canal debridement when the apical foramen was open to the external environment (Baumgartner & Mader, 1987). Therefore, it is important for the irrigation experiments to be conducted in closed systems because an open system can overestimate the efficacy and effectiveness of irrigation. The knowledge of such difference has questioned the results and clinical implications of studies that were performed in open system models. A closed system simulates the clinical situations more realistically and allows for accurate evaluation of irrigation efficacy and effectiveness when no fluid and gas exchange is allowed between root canal and external environment. A computational study investigated the effect of needle type and depth of insertion, root canal size and flow rate on the formation and elimination of AVL during conventional syringe irrigation in a combined *in-vitro* and computational fluid dynamics model. The artificial canals were shaped to size 35/04 and 50/04, open ended needle and closed ended needles were placed at WL-1 and WL-3 and irrigation with NaOCl at flow rates: 0.033 ml/s (~2.00 ml/min), 0.083 ml/s (~5.00 ml/ min), 0.166 ml/s (~10.00 ml/min) and 0.260 ml/s (15.60 ml/min) were performed. The authors of that study concluded that increasing the apical preparation size, irrigating at higher flow rate, increasing the needle insertion depth and using open-ended needles decrease the size of the resultant AVL. Moreover, the authors showed that an established AVL can be eliminated if the needle is briefly inserted to the WL while delivering the irrigant at a flow rate of 0.083 ml/s (~5.0 ml/min) and/or irrigating at 0.260 ml/s (15.60 ml/min) when the needle is held steady at WL-1 or WL-3 (Boutsioukis et al., 2014).

1.6 *Agitation during irrigation*

As previously explained, one of the shortcomings with the conventional syringe irrigation is the stagnation plane being short of the apical foramen. This may be explained by either the fluid dynamics in a closed system and/or the existence of AVL (Gulabivala et al., 2010). The second shortcoming of conventional irrigation is the laminar flow that lacks shear stresses required to remove debris and bacterial biofilms from the canal walls (Gulabivala et al., 2010). Therefore in order to improve the efficacy of irrigation in canal debridement, conventional syringe irrigation has been supplemented with methods of agitation such as sonic, ultrasonic and manual dynamic agitation (MDA) (Jiang et al., 2010). MDA is becoming more popular amongst clinicians as this technique is simple and cost effective (McGill et al., 2008). MDA involves short, gentle strokes of a well-fitting gutta percha cone to working length. The strokes are believed to remove and displace the air bubble in the apical 0-2.0 mm via hydrodynamic means (McGill et al., 2008). Moreover, repeated pull-push action can disrupt the fluid laminas through physical stretching and folding. This will allow for a better mixing of unreacted and reacted NaOCl molecules (McGill et al., 2008). MDA with three short strokes of a well-fitting gutta percha cone with amplitude of 5.0 mm has shown to result in full length penetration of a contrast agent in curved mesial canals of mandibular molars (Bronnec et al., 2010). In an *ex-vivo* experiment, root canal debridement by MDA and EndoVac system were compared, through SEM analysis, in open and closed system models. In that study, canals were shaped to 40/06, irrigant was delivered by placing the 30-gauge close-ended side vented needle at WL-4 and MDA was performed with a well-fitting gutta percha cone at 100 strokes/min. The authors reported a difference in smear layer and debris removal between open and closed system models when MDA was used whereas EndoVac performed equally effective in both systems (Parente et al., 2010). In another study, passive ultrasonic irrigation performed inferior to MDA and CWAIS (continuous warm activated irrigation and evacuation system) at WL-1 and WL-3 in removing pulp remnants from the isthmi in mandibular molar canals (Neelakantan et al., 2016). Also MDA (100 strokes) proved to be more effective than RinseEndo (pressure suction technology) in the removal of stained collagen bio-molecular film from the root canal walls (McGill et al., 2008). Therefore, MDA with a well-fitting gutta percha cone may be a simple technique to improve apical flow of the irrigant by displacing the so-called “Apical vapor lock”.

Chapter 2: Rationale and Hypotheses

2.1 Rationale

To the best of our knowledge, the effects of apical preparation size, choice of rotary file system and needle insertion depth on the presence of apical vapor lock after positive pressure irrigation have not been investigated. Also, the effects of the aforementioned factors on the elimination of apical vapor lock by manual dynamic agitation with a well-fitting gutta percha cone to working length have not been examined. Also, this study, for the first time, aims to investigate the replacement of a radiographic contrast solution by positive pressure irrigation after the elimination of apical vapor lock in a closed system model.

2.2 Hypotheses

1) Presence of apical vapor lock changes based on apical preparation size, tapering of the canal system and needle insertion depth.

2) Manual dynamic agitation is effective in removing the apical vapor lock and its efficacy depends on apical preparation size, tapering of the canal system and needle insertion depth.

3) Complete replacement of the contrast solution after elimination of apical vapor lock depends on apical preparation size, tapering of the canal system, needle insertion depth and flow rate.

2.3 Aims

1) To detect radiographically the presence of apical vapor lock after positive pressure irrigation into a dry canal when irrigation needle is placed at 1.0 mm and 3.0 mm short of working length in closed end root canal systems that are shaped with either Vortex Blue (25/04 & 30/04) or ProTaper Gold (F2 -25/08 & F3-30/09).

2) To evaluate the elimination of apical vapor lock by manual dynamic agitation with 50 strokes of a well-fitting gutta percha cone to working length for 35 seconds.

3) To investigate the replacement of the contrast solution with 6.0% NaOCl by positive pressure irrigation at two different flow rates, 2.0 ml/min (~0.033 ml/s) and 4.0 ml/min (~0.067 ml/s), and at two different needle insertion depths, 1.0 mm and 3.0 mm short of working length, after the elimination of apical vapor lock.

Chapter 3: Materials and Methods

3.1 *Pilot Experiments*

A series of pilot experiments were performed, prior to the main investigation, to seek answers to following three questions:

Question 1: What is the required amount of contrast agent (cesium chloride) in 6.0% NaOCl mixture that can provide adequate radiographic contrast with no significant observable effect on the solvent effect, dentin wettability and surface tension properties of pure 6.0%NaOCl?

In this study, cesium Chloride (CsCl; BioUltra, Sigma-Aldrich, St. Louis, MO) was used as the contrast radiography agent. 10.0% solution was initially prepared by mixing 1.0 gram of CsCl in 10.0 ml of 6.0% NaOCl. The prepared mix was then delivered into the canal system of a sample tooth (shaped to size 25/04) using a 30-gauge open-ended NaviTip needle (Ultradent, South Jordan, UT). Bucco-lingual (BL) periapical radiograph using photostimulable phosphorous (PSP) plate was taken to visualize the radiographic contrast of the solution. The concentration of CsCl in the mixture was increased by 10.0% each time until at 40.0% an adequate contrast could be visualized on periapical radiographs. The 40.0% contrast solution was prepared by mixing 4.0 gram of CsCl into

10.0 ml of 6.0% NaOCl. This contrast allowed for easy differentiation between the mixture and dentin and the presence of any existing air bubble/AVL. Next step in the pilot experiment was to exclude any significant difference in the dissolving effect and the dentin wettability between the contrast solution and pure 6.0% NaOCl. The solvent effect of pure 6.0% NaOCl and 40.0% contrast solution was compared by adding 2.0 ml of each in a petri dish and observing its efficiency and efficacy in dissolving 0.002 gram of minced white meat (chicken meat) under the operating dental microscope (Global Surgical, St. Louis, MO). In order to measure any difference in the dentin wettability between the contrast solution and pure 6.0% NaOCl, the contact angle between the contrast solution and dentin was compared with that of pure 6.0% NaOCl and dentin. Two samples of radicular dentin (2.0 mm by 2.0 mm by 1.0 mm) were sectioned from the coronal third of a mandibular distal root. A drop of contrast solution and pure 6.0% NaOCl was placed on each dentin sample using an irrigation needle. Photos were then taken under the operating dental microscope to analyze the difference in the contact angle that the mixture and pure 6.0% NaOCl made with the surface (Figure 5.2). Higher concentrations of CsCl at 45.0% and 50.0% in the mixture although enhanced the contrast but significantly decreased the contact angle between the contrast solution and dentin compared to that between pure 6.0% NaOCl and dentin.

Question 2*: Is there a difference in the penetration of contrast solution between 30-gauge close-ended side-vented and 31-gauge close-ended double side-port needle?*

A total of ten teeth were randomly selected from the main pool of experimental samples with a closed system design (shaped to either to 25/04 or 25/08). 1.0 ml of the contrast mixture was delivered at a flow rate of 3.0 ml/min (0.05 ml/s) using 31-gauge closed-ended double side-port (NaviTip, Ultradent, South Jordan, UT) at WL-1. Bucco-lingual (BL) periapical radiograph was taken by using PSP plates. Each canal was rinsed with saline, dried with paper points and the mixture solution was again delivered at the flow rate of 3.0 ml/min by 31-gauge close-ended double side-port needle at WL-3. BL periapical radiograph was then taken. To investigate the irrigation penetration using a 30-gauge close-ended side vented needle (ProRinse, Dentsply Sirona, York, PA), the same aforementioned steps were repeated. Therefore there were four irrigation experiments performed in the same tooth, two experiments with 30-gauge close-ended side vented needle placed at WL-1 and WL-3 and two experiments with 31-gauge close-ended double side-port needle placed at WL-1 and WL-3. Examination of the periapical radiographs determined no significant difference between the two types of needles with respect to the penetration of the contrast solution.

Question 3: How does manual dynamic agitation with 10 strokes, 40 strokes and 50 strokes of a well-fitting gutta percha cone to working length affect apical vapor lock elimination?

To determine whether there is a difference in the effectiveness of MDA with different numbers of strokes (10 strokes for 7 seconds, 40 strokes for 28 seconds, or 50 strokes for 35 seconds), twelve teeth with closed foramina were randomly chosen from a pool of teeth that were shaped with the following rotary file systems: Vortex Blue 25/04 & 30/04 (Dentsply Sirona, York, PA), PTG F2-25/08 & F3-30/09 (Dentsply Sirona, York, PA). More details on the closed system design will be provided in the “main investigation” subsection. For each tooth, a well-fitting gutta perch cone to WL with an adequate tug back was selected.

The following experimental steps were conducted in each tooth:

- One operator performed all the experiments.

- 31-gauge close-ended double side-port needle was used for the delivery of the irrigant.
- Flow rate was not automated; A digital stopwatch for measuring the flow rate and a 3.0 ml syringe for maintaining a constant flow rate were used for each experiment.
- Position of the radiographic apparatus remained unchanged for each experimental tooth.
- Periapical radiographs were taken using PSP plates.
- Strokes were made with a well-fitting gutta percha cone to WL.

1- 1.0 ml of contrast solution was delivered at the non-automated flow rate of 3.0 ml/min (0.05 ml/s) at WL-1→BL radiograph was taken to visualize the presence/absence of AVL.

2- In teeth with apical vapor lock, 10 vertical strokes were made with amplitude of 2-3 mm for 7 seconds→BL periapical radiograph was taken.

3- The canal was then rinsed with sterile water and dried with paper points.

4- 1.0 ml of contrast solution was delivered at the non-automated flow rate of 3.0 ml/min (0.05 ml/s) at WL-1→BL radiograph was taken to visualize presence/absence of AVL.

5- In teeth with apical vapor lock, 40 vertical strokes were made with amplitude of 2-3 mm for 28 seconds→ BL periapical radiograph was taken.

6- The canal was rinsed with sterile water and dried with paper points.

7- 1.0 ml of contrast solution was delivered at the non-automated flow rate of 3.0 ml/min (0.05 ml/s) at WL-1→BL radiograph was taken to visualize presence/absence of AVL.

8- In teeth with apical vapor lock, 50 vertical strokes were made with amplitude of 2-3 mm for 35 seconds→BL periapical radiograph was taken.

9- To analyze the efficacy of MDA with varied number of strokes when contrast solution was delivered at WL-3, steps 1-8 were repeated in each tooth while placing the irrigation needle at WL-3 instead of WL-1. The details of the findings will be presented in the "results" section. However, since 50 strokes statistically increased incidence of elimination of AVL when compared to 10 and 40 strokes, 50 strokes was selected as the fixed number of strokes to be used in the main study.

3.2 *Main Investigation*

Sample preparation:

Twenty-eight single-rooted teeth (single canals with mature roots, no caries, no resorption, free of any visible calculus or attached soft tissue) were collected and preserved in saline at +4^{o}C. In order to ensure presence of single canal system (Vertucci class I), mesio-distal (MD) and BL periapical radiographs were taken of each tooth. All teeth were decoronated to give a standard length of 15 mm. The working lengths were set at 14.5 mm, 0.5 mm short of the apical foramen. This was confirmed by placing an ISO size 10 K file (Mani, Japan) and extending it until it was visible at the apical foramen under the dental operating microscope. The pool of 28 decoronated teeth were then randomly allocated to two groups: Vortex Blue and ProTaper Gold. The random assignment was done by choosing the teeth without looking at the preoperative radiographs one day after the radiographs were taken. In order to increase the experimental efficiency, a simple model was created. This model consisted of a synthetic sponge in which one incomplete cut was made to divide the sponge into two equal sections. One side was then divided by another incomplete cut into two sections in each one tooth could be placed; therefore, there were two teeth in one sponge (Figure 3.1). The incomplete cuts also served as slits to hold the PSP plates for taking the radiographs (Figure 3.1). Prior to placement of teeth in the sponge, each tooth was first converted into a closed system. In this study, the closed system design closely followed that of Tay et al. (2010) with some modifications to prevent the ingress of hot glue into the canal system from the apical foramen. Prior to closing the apical foramen with hot glue, each experimental tooth was fully instrumented to either VB 25/04 or PTG F2 (25/08) following the manufacturer recommended protocol. No irrigant was used during instrumentation. After full instrumentation, the matching gutta percha cone from each system (VB and PTG) was inserted in the canal system and the tug back was checked. The adequacy of length of each gutta percha cone was also confirmed under the dental operating microscope. Before application of the hot glue to create a closed system, debris was pushed out from inside the canal by using a 10 K file to mask the apical foramen. A thin layer of vaseline was placed on the apical end of each gutta percha cone before its insertion to WL to minimize its adhesion to the hot glue. Both the dentinal debris and gutta percha cone prevented the movement of hot glue into the canal system. Moreover, each tooth was coated by nail varnish, except in the apical 2.0 mm, to ensure closing of any possible accessory canals that could not be detected radio-graphically. After drying of the nail varnish, hot glue was applied on the apical 4-5 mm, (Figure 3.2), while holding each tooth vertically to minimize the force of gravity pushing the glue into the canal system. After sufficient cooling of the hot glue, each tooth was placed in the sponge model. Then the surface between each tooth and the sponge was covered with OpalDam (Ultradent, South Jordan, UT) in order to close up any existing gaps (Fig. 3.1). This prevented the flow of contrast solution into the sponge during the experiments and minimized any untoward radiographic effect. For each tooth, a well-fitting gutta perch cone (from the matching system) to WL with adequate tug back was selected.

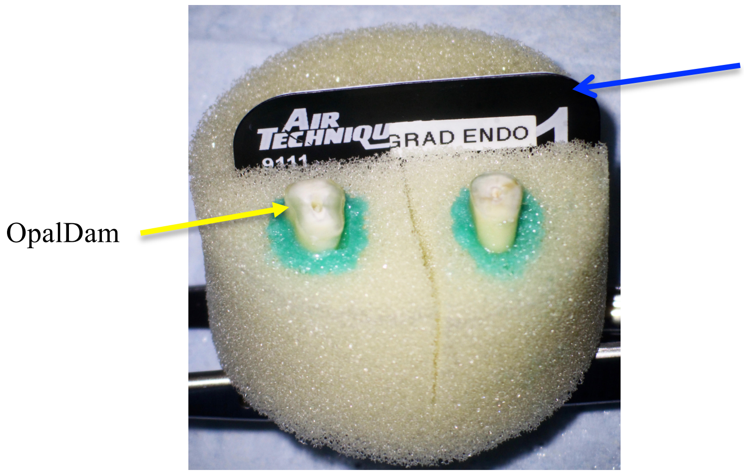


Figure 3.1. A photo of an experimental model with two teeth placed inside the sponge and a PSP plate (*blue arrow*) positioned for taking periapical radiographs- *Yellow arrow* points to the OpalDam that has filled the coronal gap between the tooth and the sponge

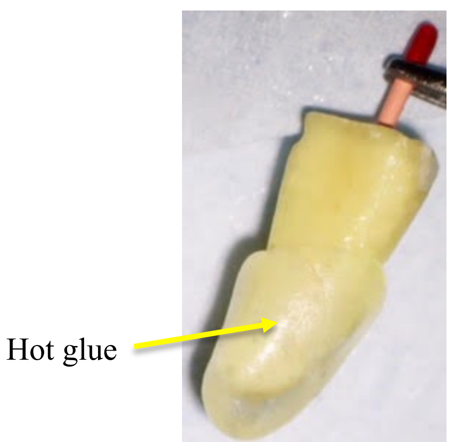


Figure 3.2. A photo of an experimental tooth after application of the hot glue (*yellow arrow*) around the apex

Irrigation, Agitation and Irrigant replacement experiments

- One operator performed all the experiments.
- 31-gauge close-ended double side-port needle was used for the delivery of the irrigant.
- Flow rate was not automated; A digital stopwatch for measuring the flow rate and a 3.0 ml syringe for maintaining a constant flow rate were used for each experiment.
- Position of the radiographic apparatus was kept unchanged for each experimental tooth.
- Periapical radiographs were taken using PSP plates.

Detection of apical vapor lock after PPI at WL-1

1: In each tooth, 1.0 ml of contrast solution was delivered at the flow rate of 3.0 ml/min (0.05 ml/s) at WL-1→BL radiograph was taken to visualize the presence/absence of AVL.

2: Teeth in which no AVL was present and contrast solution had penetrated the full length of canal system→ continued to step 5.

Manual dynamic agitation with 50 strokes

3: Teeth in which AVL was present→50 strokes of a well-fitting gutta percha cone to WL with amplitude of 2-3 mm were performed for 35 seconds→ BL periapical radiograph was taken.

4: Teeth in which AVL was not eliminated → continued to step 8

Replacement of contrast solution by PPI at 2.0 ml/min at WL-1 after elimination of AVL

5: Teeth in which AVL was eliminated either by PPI or MDA→ 1.0 ml of pure 6.0% NaOCl was delivered at the flow rate of 2.0 ml/min (~0.033 ml/s) at WL-1→ BL periapical radiograph was taken.

Replacement of contrast solution by PPI at 4.0 ml/min at WL-1 after elimination of AVL

6: Teeth in which contrast solution was not replaced by PPI at 2.0 ml/min→ 1.0 ml of pure 6.0% NaOCl was delivered at the flow rate of 4.0 ml/min (~0.067 ml/s) at WL-1→ BL periapical radiograph was taken.

7. Teeth in which contrast solution was completely replaced by PPI at 2.0 ml/min→ Canal was dried using paper points, a 30-gauge open-ended NaviTip needle (Ultradent- South Jordan, UT) was placed at WL and 0.2 ml of contrast solution was delivered→ BL periapical radiograph was taken to ensure presence of no AVL→ 1.0 ml of pure 6.0% NaOCl was delivered at the flow rate of 4.0 ml/min (~0.067 ml/s) at WL-1→ BL periapical radiograph was taken.

8: Each canal was rinsed with sterile water and dried by paper points.

Detection of AVL after PPI at WL-3

9: In each tooth, 1.0 ml of contrast solution was delivered at the flow rate of 3.0 ml/min (0.05 ml/s) at WL-3→BL radiograph was taken to visualize the presence/absence of AVL.

10: Teeth in which no AVL was present and contrast solution had penetrated the full length of canal system→ continued to step 13.

Manual dynamic agitation with 50 strokes

11: Teeth in which AVL was present→50 strokes of a well-fitting gutta percha cone to WL with amplitude of 2-3 mm were performed for 35 seconds→ BL periapical radiograph was taken.

12: Teeth in which AVL was not eliminated→continued to step 16.

Replacement of contrast solution by PPI at 2.0 ml/min at WL-3 after elimination of AVL

13: Teeth in which AVL was eliminated either by PPI or MDA→1.0 ml of pure 6.0% NaOCl was delivered at the flow rate of 2.0 ml/min (~0.033 ml/s) at WL-3→ BL periapical radiograph was taken.

Replacement of contrast solution by PPI at 4.0 ml/min at WL-3 after elimination of AVL

14: Teeth in which contrast solution was not replaced by PPI at 2.0 ml/min at WL-3→1.0 ml of pure 6.0% NaOCl was delivered at the flow rate of 4.0 ml/min (~0.067 ml/s) at WL-3→BL periapical radiograph was taken.

15: Teeth in which contrast solution was completely replaced by PPI at 2.0 ml/min→ each tooth was dried using paper points, a 30-gauge open-ended NaviTip needle (Ultradent- South Jordan, UT) was placed at WL and 0.2 ml of contrast solution was delivered→BL periapical radiograph was taken to ensure presence of AVL→ 1.0 ml of pure 6.0% NaOCl was delivered at the flow rate of 4.0 ml/min (~0.067 ml/s) at WL-3→ BL periapical radiograph was taken

Shaping to either VB 30/04 or PTG 30/09

16: Each tooth served as its control and was shaped from VB 25/04 to VB 30/04 and from PTG F2 (25/08) to PTG F3 (30/09)→ All the aforementioned steps 1-15 were repeated in each tooth.

Statistical analyses

All analyses were performed using the SPSS Version 25.0 Software. Chi-square test was used to compare proportion and logistic regression analysis was used to test multiple predictors in association with dependent variables of the present study. The threshold for statistical significance for all tests was set at $p \leq 0.050$.

Chapter 4: Results

4.1 Number of strokes and their effect on the elimination of apical vapor lock by manual dynamic agitation (*Pilot experiment question #3):*

In total, 24 experiments were performed for each category of strokes as shown in Table 4.1. The results indicated that 10, 40 and 50 strokes eliminated AVL in 5/24 (20.8%), 10/24 (41.7%) and 23/24 (95.8%) of the experiments respectively (Table 4.2). The difference among the three sets of strokes and their effect on the elimination of AVL was statistically significant (p= 0.001).

The multivariate analysis was highly significant (p<0.001) and showed that 43.8% (Nagelkerke R Square: 0.438x100) of the variance in the elimination of AVL can be explained by apical preparation size, type of rotary file system, depth of needle insertion and number of strokes (Table 4.4). Shaping the root canal system with VB and placing the needle closer to the working length also had the joint effect on the elimination of AVL when controlled for other predictors in the logistic regression model (Table 4.4).

Table 4.1. Elimination of apical vapor lock by manual dynamic agitation with 10, 40 and 50 strokes of a well-fitting gutta percha cone to working length

Tooth#	Apical Size	Rotary system	Needle placement	Elimination of apical vapor lock with 10 strokes	Elimination of apical vapor lock with 40 strokes	Elimination of apical vapor lock with 50 strokes
P.1	25	VB	WL-1	Yes	Yes	Yes
P.1	25	VB	WL-3	No	No	Yes
P.2	25	VB	WL-1	No	No	Yes
P.2	25	VB	WL-3	No	No	Yes
P.3	30	VB	WL-1	Yes	Yes	Yes
P.3	30	VB	WL-3	No	No	Yes
P.4	30	VB	WL-1	No	No	Yes
P.4	30	VB	WL-3	No	No	Yes
P.5	30	VB	WL-1	No	No	Yes
P.5	30	VB	WL-3	Yes	Yes	Yes
P.6	30	VB	WL-1	No	Yes	Yes
P.6	30	VB	WL-3	No	Yes	Yes
P.7	25	PTG	WL-1	No	No	Yes
P.7	25	PTG	WL-3	No	Yes	Yes
P.8	25	PTG	WL-1	Yes	Yes	Yes
P.8	25	PTG	WL-3	No	No	No
P.9	30	PTG	WL-1	No	No	Yes
P.9	30	PTG	WL-3	No	No	Yes
P.10	30	PTG	WL-1	No	Yes	Yes
P.10	30	PTG	WL-3	No	Yes	Yes
P.11	30	PTG	WL-1	No	No	Yes

Tooth#	Apical Size	Rotary system	Needle placement	Elimination of apical vapor lock with 10 strokes	Elimination of apical vapor lock with 40 strokes	Elimination of apical vapor lock with 50 strokes
P.11	30	PTG	WL-3	**No**	**No**	**Yes**
P.12	30	PTG	WL-1	**Yes**	**Yes**	**Yes**
P.12	30	PTG	WL-3	**No**	**No**	**Yes**

Table 4.2. Elimination of apical vapor lock by manual dynamic agitation with 10, 40 and 50 strokes of a well-fitting gutta percha cone to working length

	Elimination of apical vapor lock	
	No	**Yes**
10 Strokes	19/24 (79.2%)	5/24 (20.8%)
40 Strokes	14/24 (58.3%)	10/24 (41.7%)
50 Strokes	1/24 (4.2%)	23/24 (95.8%)
Total	34/72 (47.2%)	38/72 (52.8%)

Table 4.3. Predictors of elimination of apical vapor lock after manual dynamic agitation with a well-fitting gutta percha cone to working length (Bivariate analyses)

Predictors		**Eelimination of apical vapor lock**		***p*-value #**
		No	**Yes**	
Apical size	**25**	12/24 (50.0%)	12/24(50.0%)	0.738
	30	22/48 (45.8%)	26/48 (54.2%)	
Rotary system	**VB**	16/36 (44.4%)	20/36 (55.6%)	0.637
	PTG	18/36 (50.0%)	18/36 (50.0%)	
Needle placement	**WL-1**	14/36 (38.9%)	22/36 (61.1%)	0.157
	WL-3	20/36 (55.6%)	16/36 (44.4%)	
Strokes	**10**	19/24 (79.2%)	5/24 (20.8%)	0.001
	40	14/24 (58.3%)	10/24 (41.7%)	
	50	1/24 (4.2%)	23/24 (95.8%)	

Chi-square test

Table 4.4. Predictors of elimination of apical vapor lock by manual dynamic agitation with a well-fitting gutta percha cone to working length (Multivariate analysis)

Model Summary				
Nagelkerke R Square: 0.438, $p < 0.001$				
Predictors	**Odds ratio**	***p*-value #**	**95% CI** Lower	Upper
Apical size (0=25, 1=30)	0.8	0.652	0.3	2.4
Rotary system (0=VB, 1=PTG)	0.3	0.004	0.1	0.7
Needle placement (0=1mm, 1= 3mm)	0.3	0.026	0.1	0.9
Strokes (0=10, 1=40, 2=50)	5.0	0.001	2.3	10.7

logistic regression

4.2 Detection of apical vapor lock *(Hypothesis #1)*

To examine the presence of AVL after PPI, 112 experiments were performed in 28 teeth. Each tooth was subjected to four different experiments as shown in tables 4.5 and 4.6. AVL was present in 103/112 (92.0%) of the samples (Table 4.7) (Figure 4.1B). In majority of the experimental teeth with AVL, a general radiographic observation indicated that the contrast solution failed to travel beyond the needle tip (Figure 4.2). In 9/112 (8.0%) of the samples, the contrast solution penetrated the full length of the canal system and therefore no AVL was present (Table 4.7) (Figure 4.1A). Bivariate analyses showed that there were no statistically significant differences between the two apical preparation sizes (25 vs. 30, $p= 0.728$), the two rotary file systems (VB vs. PTG, $p= 0.728$)

and the two needle insertion depths (WL-1 vs. WL-3, $p = 0.297$) with regards to the presence of AVL after PPI (Table 4.8). The overall logistic regression multivariate model was highly significant ($p < 0.001$) and showed that 73.0% (Nagelkerke R Square: 0.73x100) of the variance predicting the presence of AVL can be attributed to the joint effect of three tested predictors: apical preparation size, rotary file system and needle insertion depth (Table 4.9). As compared to the other two predictors, PTG rotary file system had the strongest effect size (OR= 5.2, $p = 0.001$) with regards to the presence of AVL after PPI (Table 4.9). AVL was more likely to be present in teeth that were shaped with PTG compared to teeth that were shaped with VB when apical preparation size and needle insertion depths were controlled for (Table 4.9).

Table 4.5. Presence of apical vapor lock after positive pressure irrigation with the contrast solution in experimental teeth shaped with Vortex Blue 25/04 & 30/04

Tooth# (Rotary system/ Apical size/ Needle placement)	Apical vapor lock present	Tooth# (Rotary system/ Apical size/Needle placement)		Tooth# (Rotary system/ Apical size/ Needle placement)	Apical vapor lock present	Tooth# (Rotary system/ Apical size/Needle placement)
1 (VB /25/ WL-1)	Yes Yes	1 (VB /25 / WL-3)		8 (VB /25 / WL-1)	Yes Yes	8 (VB /25 / WL-3)
1 (VB /30 / WL-1)	Yes Yes	1 (VB /30 / WL-3)		8 (VB /30 / WL-1)	Yes Yes	8 (VB /30 / WL-3)
2 (VB /25 / WL-1)	Yes Yes	2 (VB /25 / WL-3)		9 (VB /25 / WL-1)	Yes Yes	9 (VB /25 / WL-3)
2 (VB /30 / WL-1)	Yes Yes	2 (VB /30 / WL-3)		9 (VB /30/ WL-1)	Yes Yes	9 (VB /30 / WL-3)
3 (VB /25 / WL-1)	Yes Yes	3 (VB /25 / WL-3)		10 (VB /25 / WL-1)	Yes Yes	10 (VB /25 / WL-3)
3 (VB /30 / WL-1)	Yes Yes	3 (VB /30 / WL-3)		10 (VB /30 / WL-1)	Yes Yes	10 (VB /30 / WL-3)
4 (VB /25 / WL-1)	Yes Yes	4 (VB /25 / WL-3)		11 (VB /25 / WL-1)	Yes Yes	10 (VB /25 / WL-3)
4 (VB /30 / WL-1)	Yes Yes	4 (VB /30 / WL-3)		11 (VB /30 / WL-1)	Yes Yes	11 (VB /30 / WL-3)
5 (VB /25 / WL-1)	Yes No	5 (VB /25 / WL-3)		12 (VB /25 / WL-1)	Yes Yes	12 (VB /25 / WL-3)
5 (VB /30 / WL-1)	Yes Yes	5 (VB /30 / WL-3)		12 (VB /30 / WL-1)	Yes Yes	12 (VB /30 / WL-3)
6 (VB /25 / WL-1)	No Yes	6 (VB /25 / WL-3)		13 (VB /25 / WL-1)	Yes Yes	13 (VB /25 / WL-3)
6 (VB /30 / WL-3)	No Yes	6 (VB /30 / WL-3)		13 (VB /30 / WL-1)	Yes Yes	13 (VB /30 / WL-3)
7 (VB /25 / WL-1)	No Yes	7 (VB /25 / WL-3)		14 (VB /25 / WL-1)	Yes Yes	14 (VB /25 / WL-3)
7 (VB /30 / WL-1)	No Yes	7 (VB /30 / WL-3)		14 (VB /30 / WL-1)	Yes Yes	14 (VB /30 / WL-3)

Table 4.6. Presence of apical vapor lock after positive pressure irrigation with the contrast solution in experimental teeth shaped with ProTaper Gold F2-25/08 & F3-30/09

Tooth# (Rotary system/ Apical size / Needle placement)	Apical vapor lock present		Tooth# (Rotary system/ Apical size / Needle placement)		Tooth# (Rotary system/ Apical size / Needle placement)	Apical vapor lock present		Tooth# (Rotary system/ Apical size / Needle placement)
15 (PTG /25/ WL-1)	Yes	Yes	15 (PTG /25/ WL-3)		22 (PTG /25/ WL-1)	Yes	Yes	22 (PTG /25/ WL-3)
15 (PTG /30/ WL-1)	Yes	Yes	15 (PTG /30/ WL-3)		22 (PTG /30/ WL-1)	Yes	Yes	22 (PTG /30/ WL-3)
16 (PTG /25/ WL-1)	Yes	Yes	16 (PTG /25/ WL-3)		23 (PTG /25/ WL-1)	Yes	Yes	23 (PTG /25/ WL-3)
16 (PTG /30/ WL-1)	Yes	Yes	16 (PTG /30/ WL-3)		23 (PTG /30/ WL-1)	Yes	Yes	23 (PTG /30/ WL-3)
17 (PTG /25/ WL-1)	Yes	Yes	17 (PTG /25/ WL-3)		24 (PTG /25/ WL-1)	Yes	Yes	24 (PTG /25/ WL-3)
17 (PTG /30/ WL-1)	No	Yes	17 (PTG /30/ WL-3)		24 (PTG /30/ WL-1)	Yes	Yes	24 (PTG /30/ WL-3)
18 (PTG /25/ WL-1)	Yes	No	18 (PTG /25/ WL-3)		25 (PTG /25/ WL-1)	Yes	Yes	25 (PTG /25/ WL-3)
18 (PTG /30/ WL-1)	Yes	No	18 (PTG /30/ WL-3)		25 (PTG /30/ WL-1)	Yes	Yes	25 (PTG /30/ WL-3)
19 (PTG /25/ WL-1)	Yes	Yes	19 (PTG /25/ WL-3)		26 (PTG /25/ WL-1)	Yes	Yes	26 (PTG /25/ WL-3)
19 (PTG /30/ WL-1)	Yes	Yes	19 (PTG /30/ WL-3)		26 (PTG /30/ WL-1)	Yes	Yes	26 (PTG /30/ WL-3)
20 (PTG /25/ WL-1)	Yes	Yes	20 (PTG /25/ WL-3)		27 (PTG /25/ WL-1)	Yes	Yes	27 (PTG /25/ WL-3)
20 (PTG /30/ WL-1)	Yes	Yes	20 (PTG /30/ WL-3)		27 (PTG /30/ WL-1)	No	Yes	27 (PTG /30/ WL-3)
21 (PTG /25/ WL-1)	Yes	Yes	21 (PTG /25/ WL-3)		28 (PTG /25/ WL-1)	Yes	Yes	28 (PTG /25/ WL-3)
21 (PTG /30/ WL-1)	Yes	Yes	21 (PTG /30/ WL-3)		28 (PTG /30/ WL-1)	Yes	Yes	28 (PTG /30/ WL-3)

Table 4.7. Presence of apical vapor lock after positive pressure irrigation

Presence of apical vapor lock	
No	Yes
9/112 (8.0%)	103/112 (92.0%)

Table 4.8. Predictors of apical vapor lock after positive pressure irrigation (Bivariate analyses)

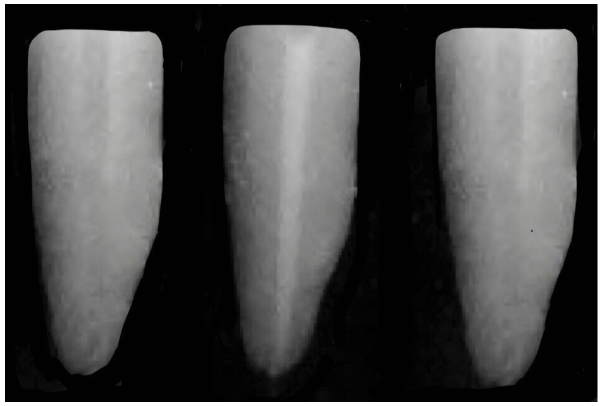
Predictors		Apical vapor lock presence		*p*-value #
		No	Yes	
Apical size	**25**	4/56 (7.1%)	52/56 (92.9%)	0.728
	30	5/56 (8.9%)	51/56 (91.1%)	
Rotary system	**VB**	5/56 (8.90%)	52/56(91.1%)	0.728
	PTG	4/56 (7.10%)	52/56 (92.9%)	
Needle placement	**WL-1**	3/56 (5.4%)	53/56 (94.6%)	0.297
	WL-3	6/56 (10.7%)	50/56 (89.3%)	

Chi-square test

Table 4.9. Predictors of apical vapor lock after positive pressure irrigation (Multivariate analysis)

Model Summary **Nagelkerke R Square:** 0.730, $p<0.001$				
Predictors	**Odds ratio**	***p*-value #**	**95% CI** Lower	 Upper
Apical size (0=25, 1=30)	1.2	0.733	0.4	4.2
Rotary system (0= VB, 1=PTG)	5.2	0.001	2.4	11.6
Needle placement (0=3mm, 1=1mm)	0.8	0.737	0.2	2.7

Logistic regression



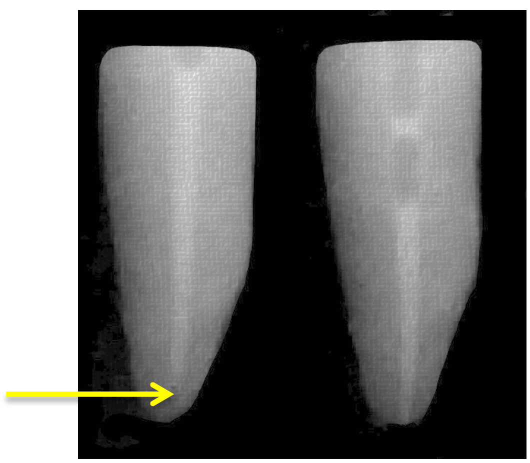
A1 **A2** **A3**

Figure 4.1 A. Absence of apical vapor lock and replacement of the contrast solution by positive pressure irrigation in a tooth shaped with Vortex Blue 25/04

A1: Tooth shaped with VB 25/04

A2: Absence of AVL after PPI at WL-1

A3: Complete replacement of the contrast solution with pure 6.0% NaOCl by PPI at the flow rate: 2.0 ml/min and at WL-1

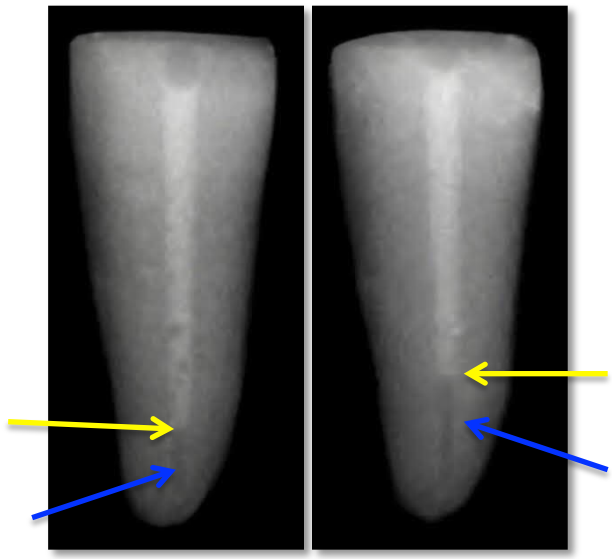


B1 **B2**

Figure 4.1 B. Presence and elimination of apical vapor lock by manual dynamic agitation in a tooth shaped with Vortex Blue 30/04

B1: AVL (*yellow arrow*) after PPI at WL-1

B2: Elimination of AVL by MDA with 50 strokes of a well-fitting gutta percha cone to WL



A1 **A2**

Figure 4.2. Penetration of the contrast solution short of needle tip (*yellow arrows)* and presence of apical vapor lock (*blue arrows*) after positive pressure irrigation at **(A1)** 1.0 mm and **(A2)** 3.0 mm from working length in a tooth shaped with ProTaper Gold F3 (30/09)

4.3 Elimination of apical vapor lock by manual dynamic agitation with 50 strokes of a well-fitting gutta percha cone to working length (*Hypothesis #2*)

To test the efficacy of MDA with 50 strokes of a well-fitting gutta percha cone in eliminating AVL, a total of 103 experiments were performed as shown in tables 4.10 and 4.11. AVL was eliminated successfully in 81.6% of the experiments (Table 4.12). Examples of complete and in-complete elimination of AVL are shown in figures 4.3A-B and 4.3C-D respectively.

Bivariate analyses showed that there were no statistically significant differences with regards to the elimination of AVL by MDA between the two apical preparation sizes (25 vs. 30, p= 0.419), the two rotary file systems (VB vs. PTG, p= 0.083) and the two needle insertion depths (WL-1 vs. WL-3, p= 0.910).

The overall multivariate logistic regression model with three potential predictors (apical preparation size, type of rotary file system and needle insertion depth) was highly significant *(p*< 0.001) and showed that 39.3% (Nagelkerke R Square: 0.393x100) of variance in elimination of AVL can be explained by the joint effect of three aforementioned predictors (Table 4.14). When controlled for the other two tested predictors, teeth that were shaped with PTG as compared to with VB were associated with an increased likelihood (OR= 1.9, *p*= 0.007) of elimination of AVL when subjected to 50 strokes (Table 4.14). Also in order to include the nine teeth in which no AVL was present after positive pressure irrigation, another statistical analysis was performed. In this multivariate analysis, natural elimination of AVL by PPI was included as one of the predictors for the overall outcome of “apical vapor lock elimination”. This inclusion showed that 46.8%, (Nagelkerke R Square 0.468x100) of the variance in elimination of AVL can be explained by the joint effect of four tested predictors: apical preparation size, rotary file system, needle placement and natural elimination by PPI (Table 4.15). The difference of explained variance between the two logistic models indicates that natural elimination of apical vapor lock is around 7.5% when controlled for three factors, namely apical preparation size, rotary file system and depth of needle insertion.

Table 4.10. Elimination of apical vapor lock by manual dynamic agitation with 50 strokes of a well-fitting gutta percha cone to working length in teeth shaped with Vortex Blue 25/04 & 30/04

Tooth# (Rotary system/ Apical size/ Needle placement)	Apical vapor lock elimination		Tooth# (Rotary system/ Apical size/Needle placement)		Tooth# (Rotary system/ Apical size/ Needle placement)	Apical vapor lock elimination		Tooth# (Rotary system/ Apical size/Needle placement)
1 (VB /25/ WL-1)	Yes	Yes	1 (VB /25/ WL-3)		8 (VB /25/ WL-1)	No	No	8 (VB /25./ WL-3)
1 (VB /30/ WL-1)	Yes	Yes	1 (VB /30/ WL-3)		8 (VB /30/ WL-1)	No	No	8 (VB /30/ WL-3)
2 (VB /25/ WL-1)	Yes	Yes	2 (VB /25/ WL-3)		9 (VB /25/ WL-1)	Yes	Yes	9 (VB /25/ WL-3)
2 (VB /30/ WL-1)	Yes	Yes	2 (VB /30/ WL-3)		9 (VB /30/ WL-1)	Yes	Yes	9 (VB /30/ WL-3)
3 (VB /25/ WL-1)	Yes	Yes	3 (VB /25/ WL-3)		10 (VB /25/ WL-1)	Yes	Yes	10 (VB /25/ WL-3)
3 (VB /30/ WL-1)	Yes	Yes	3 (VB /30/ WL-3)		10 (VB /30/ WL-1)	Yes	Yes	10 (VB /30/ WL-3)
4 (VB /25/ WL-1)	Yes	Yes	4 (VB /25/ WL-3)		11 (VB /25/ WL-1)	Yes	Yes	10 (VB /25/ WL-3)
4 (VB /30/ WL-1)	Yes	Yes	4 (VB /30/ WL-3)		11 (VB /30/ WL-1)	Yes	Yes	11 (VB /30/ WL-3)
5 (VB /25/ WL-1)	Yes	X	5 (VB /25/ WL-3)		12 (VB /25/ WL-1)	Yes	Yes	12 (VB /25/ WL-3)
5 (VB /30/ WL-1)	No	No	5 (VB /30/ WL-3)		12 (VB /30/ WL-1)	Yes	Yes	12 (VB /30/ WL-3)
6 (VB /25/ WL-1)	X	Yes	6 (VB /25/ WL-3)		13 (VB /25/ WL-1)	Yes	Yes	13 (VB /25/ WL-3)
6 (VB /30/ WL-1)	X	Yes	6 (VB /30/ WL-3)		13 (VB /30/ WL-1)	Yes	Yes	13 (VB /30/ WL-3)
7 (VB /25/ WL-1)	X	Yes	7 (VB /25/ WL-3)		14 (VB /25/ WL-1)	Yes	Yes	14 (VB /25/ WL-3)
7 (VB /30/ WL-1)	X	Yes	7 (VB /30/ WL-3)		14 (VB /30/ WL-1)	Yes	Yes	14 (VB /30/ WL-3)

***X:** Samples in which apical vapor lock was not present- elimination could not be measured*

Table 4.11. Elimination of apical vapor lock by manual dynamic agitation with 50 strokes of a well-fitting gutta percha cone to working length in teeth shaped with ProTaper Gold F2-25/08 & F3-30/09

Tooth# (Rotary system/ Apical size / Needle placement)	Apical vapor lock elimination	Tooth# (Rotary system/ Apical size / Needle placement)		Tooth# (Rotary system/ Apical size / Needle placement)	Apical vapor lock elimination	Tooth# (Rotary system/ Apical size / Needle placement)
15 (PTG /25/ WL-1)	Yes Yes	15 (PTG /25/ WL-3)		22 (PTG /25/ WL-1)	Yes Yes	22 (PTG /25/ WL-3)
15 (PTG /30/ WL-1)	Yes Yes	15 (PTG /30/ WL-3)		22 (PTG /30/ WL-1)	Yes Yes	22 (PTG /30/ WL-3)
16 (PTG /25/ WL-1)	Yes Yes	16 (PTG /25/ WL-3)		23 (PTG /25/ WL-1)	Yes Yes	23 (PTG /25/ WL-3)
16 (PTG /30/ WL-1)	No Yes	16 (PTG /30/ WL-3)		23 (PTG /30/ WL-1)	Yes Yes	23 (PTG /30/ WL-3)
17 (PTG /25/ WL-1)	Yes Yes	17 (PTG /25/ WL-3)		24 (PTG /25/ WL-1)	Yes Yes	24 (PTG /25/ WL-3)
17 (PTG /30/ WL-1)	X Yes	17 (PTG /30/ WL-3)		24 (PTG /30/ WL-1)	Yes Yes	24 (PTG /30/ WL-3)
18 (PTG /25/ WL-1)	Yes X	18 (PTG /25/ WL-3)		25 (PTG /25/ WL-1)	Yes Yes	25 (PTG /25/ WL-3)
18 (PTG /30/ WL-1)	Yes X	18 (PTG /30/ WL-3)		25 (PTG /30/ WL-1)	Yes Yes	25 (PTG /30/ WL-3)
19 (PTG /25/ WL-1)	No No	19 (PTG /25/ WL-3)		26 (PTG /25/ WL-1)	Yes Yes	26 (PTG /25/ WL-3)
19 (PTG /30/ WL-1)	No No	19 (PTG /30/ WL-3)		26 (PTG /30/ WL-1)	Yes No	26 (PTG /30/ WL-3)
20 (PTG /25/ WL-1)	No No	20 (PTG /25/ WL-3)		27 (PTG /25/ WL-1)	Yes Yes	27 (PTG /25/ WL-3)
20 (PTG /30/ WL-1)	Yes Yes	20 (PTG /30/ WL-3)		27 (PTG /30/ WL-1)	X No	27 (PTG /30/ WL-3)
21 (PTG /25/ WL-1)	No No	21 (PTG /25/ WL-3)		28 (PTG /25/ WL-1)	Yes Yes	28 (PTG /25/ WL-3)
21 (PTG /30/ WL-1)	No No	21 (PTG /30/ WL-3)		28 (PTG /30/ WL-1)	Yes Yes	28 (PTG /30/ WL-3)

X: *Samples in which apical vapor lock was not present- elimination could not measured*

Table 4.12. Elimination of apical vapor lock by manual dynamic agitation with 50 strokes of a well-fitting gutta percha cone to working length

Elimination of apical vapor lock	
No	**Yes**
19/103 (18.4%)	84/103 (81.6%)

Table 4.13. Predictors of elimination of apical vapor lock by manual dynamic agitation with 50 strokes of a well-fitting gutta percha cone to working length (Bivariate analyses)

Predictors		Elimination of apical vapor lock		*p*-value #
		No	**Yes**	
Apical size	**25**	8/52 (15.4%)	44/52 (84.6%)	0.419
	30	11/51 (21.6%)	40/51 (78.4%)	
Rotary system	**VB**	6/51 (11.8%)	45/51 (88.2%)	0.083
	PTG	13/52 (25.0%)	39/52 (75.0%)	
Needle placement	**WL-1**	9/50 (18.0%)	41/50 (82.0%)	0.910
	WL-3	10/53 (18.9%)	43/53 (81.1%)	

Chi-square test

Table 4.14. Predictors of elimination of apical vapor lock by manual dynamic agitation with 50 strokes of a well-fitting gutta percha cone to working length (Multivariate analysis)

Model Summary **Nagelkerke R Square:** 0.393, *p*< 0.001				
Predictors	**Odds ratio**	***p*-value #**	**95% CI** Lower	 Upper
Apical size (0=25, 1=30)	1.1	0.756	0.5	2.8
Rotary system (0=VB, 1=PTG)	1.9	0.007	1.2	3.0
Needle placement (0=3mm, 1= 1mm)	1.6	0.284	0.7	4.1

Logistic regression

Table 4.15. Predictors of elimination of apical vapor lock by manual dynamic agitation with 50 strokes of a well-fitting gutta percha cone to working length controlled for teeth with no apical vapor lock after positive pressure irrigation (Multivariate analysis)

Model Summary **Nagelkerke R Square:** 0.468, *p*< 0.001				
Predictors	**Odds ratio**	***p*-value #**	**95% CI** Lower	 Upper
Apical size (0=25, 1=30)	1.1	0.756	0.5	2.8
Rotary system (0=VB, 1=PTG)	1.9	0.007	1.2	3.0
Needle placement (0=3mm, 1= 1mm)	1.6	0.284	0.7	4.1

Logistic regression

4.4 Replacement of the contrast solution by positive pressure irrigation after elimination of apical vapor lock (*Hypothesis #3*)

In total, 181 experiments were performed at two different needle insertion depths (WL-1 and WL-3) and at two different flow rates (2.0 ml/min and 4.0 ml/min) to test for the replacement of the contrast solution in teeth in which AVL was removed either by PPI or by MDA (Tables 4.16 & 4.17). Examples of complete and incomplete replacement are provided in figures 4.3A and 4.3B respectively. Bivariate analyses showed that there were statistically significant differences between the needle insertion depths at WL-1and WL-3 (p= 0.001) and the flow rates at 2.0 ml/min and 4.0 ml/min (p= 0.001) with respect to complete replacement of the contrast solution (Table 4.18). The overall multivariate model was highly significant (p< 0.001) and showed that 56.2% (Nagelkerke R Square: 0.562x100) of variance in irrigant replacement can be explained by the three predictors: apical preparation size, rotary file system, needle insertion depth and flow rate (Table 4.19). In this model, needle insertion depth showed to be the dominating predictor. Increase in needle insertion depth (WL-1) substantially increased the likelihood of the contrast solution replacement (OR=31.9, p= 0.001) when controlled for other predictors of this model (Table 4.19). Increase in the flow rate (4.0 ml/min versus 2.0 ml/min) also significantly increased the odds of the contrast solution replacement (OR=6.3, p= 0.001) (Table 4.19). Complete replacement of the contrast solution was more likely in teeth that were shaped with VB when compared to that in teeth that were shaped with PTG (OR=0.3, p= 0.001) (Table 4.19). Decrease in the apical preparation size (25 vs. 30) was associated with an increase in the replacement of the contrast solution when other predictors of this model were controlled for (OR=0.5, p= 0.046) (Table 4.19).

Table 4.16. Replacement of the contrast solution with pure 6.0% NaOCl by positive pressure irrigation after elimination of apical vapor lock in teeth shaped with Vortex Blue 25/04 & 30/04

Tooth# (Rotary system/ Apical size / Needle placement)	Flow rate (ml/min)	Irrigant replacement		Flow rate (ml/min)	Tooth# (Rotary system/ Apical size / Needle placement)		Tooth# (Rotary system/ Apical size / Needle placement)	Flow rate (ml/min)	Irrigant replacement		Flow rate (ml/min)	Tooth# (Rotary system/ Apical size / Needle placement)
1 (VB /25/ WL-1)	2 4	Yes Yes	No No	2 4	1 (VB /25/ WL-3)		8 (VB /25/ WL-1)	2 4	X X	X X	2 4	8 (VB /25/ WL-3)
1 (VB /30/ WL-1)	2 4	Yes Yes	No No	2 4	1 (VB /30/ WL-3)		8 (VB /30/ WL-1)	2 4	X X	X X	2 4	8 (VB /30/ WL-3)
2 (VB /25/ WL-1)	2 4	Yes Yes	No No	2 4	2 (VB /25/ WL-3)		9 (VB/25/ WL-1)	2 4	Yes Yes	No Yes	2 4	9 (VB /25/ WL-3)
2 (VB /30/ WL-1)	2 4	Yes Yes	No No	2 4	2 (VB /30/ WL-3)		9 (VB /30/ WL-1)	2 4	Yes Yes	No Yes	2 4	9 (VB /30/ WL-3)
3 (VB /25/ WL-1)	2 4	Yes Yes	No No	2 4	3 (VB /25/ WL-3)		10 (VB /25/ WL-1)	2 4	Yes Yes	No No	2 4	10 (VB /25/ WL-3)
3 (VB /30/ WL-1)	2 4	Yes Yes	No No	2 4	3 (VB /30/ WL-3)		10 (VB /30/ WL-1)	2 4	No Yes	No No	2 4	10 (VB/30/ WL-3)
4 (VB /25/ WL-1)	2 4	Yes Yes	No Yes	2 4	4 (VB /25/ WL-3)		11 (VB /25/ WL-1)	2 4	No Yes	No No	2 4	11 (VB /25/ WL-3)
4 (VB /30/ WL-1)	2 4	Yes Yes	No No	2 4	4 (VB /30/ WL-3)		11 (VB /30/ WL-1)	2 4	Yes Yes	No No	2 4	11 (VB /30/ WL-3)
5 (VB /25/ WL-1)	2 4	Yes Yes	No Yes	2 4	5 (VB /25/ WL-3)		12 (VB /25/ WL-1)	2 4	No Yes	No No	2 4	12 (VB /25/ WL-3)
5 (VB /30/ WL-1)	2 4	X X	X X	2 4	5 (VB /30/ WL-3)		12 (VB /30/ WL-1)	2 4	Yes Yes	No No	2 4	12 (VB /30/ WL-3)
6 (VB /25/ WL-1)	2 4	Yes Yes	No No	2 4	6 (VB/25/ WL-3)		13 (VB /25/ WL-1)	2 4	Yes Yes	No No	2 4	13 (VB /25/ WL-3)
6 (VB/30/ WL-1)	2 4	X X	No Yes	2 4	6 (VB /30/ WL-3)		13 (VB /30/ WL-1)	2 4	Yes Yes	No No	2 4	13 (VB /30/ WL-3)
7 (VB /25/ WL-1)	2 4	Yes Yes	No Yes	2 4	7 (VB /25/ WL-3)		14 (VB /25/ WL-1)	2 4	No Yes	No No	2 4	14 (VB /25/ WL-3)
7 (VB /30/ WL-1)	2 4	No Yes	No Yes	2 4	7 (VB /30/ WL-3)		14 (VB /30/ WL-1)	2 4	No Yes	No No	2 4	14 (VB /30/ WL-3)

***X:** Samples in which apical vapor lock was not eliminated - Replacement of the contrast solution could not be measured*

Table 4.17. Replacement of the contrast solution with pure 6.0% NaOCl by positive pressure irrigation after elimination of apical vapor lock in teeth shaped with ProTaper Gold F2-25/08 & F3-30/09

Tooth# (Rotary system/ Apical size / Needle placement)	Flow rate (ml/min)	Irrigant replacement	Flow rate (ml/min)	Tooth# (Rotary system/ Apical size / Needle placement)
15 (PTG/25/ WL-1)	2 4	No No Yes No	2 4	15 (PTG/25/ WL-3)
15 (PTG/30/ WL-1)	2 4	No No Yes No	2 4	15 (PTG/30/ WL-3)
16 (PTG/25/ WL-1)	2 4	Yes No Yes No	2 4	16 (PTG/25/ WL-3)
16 (PTG/30/ WL-1)	2 4	X No Yes No	2 4	16 (PTG/30/ WL-3)
17 (PTG/25/ WL-1)	2 4	Yes No Yes Yes	2 4	17 (PTG/25/ WL-3)
17 (PTG/30/ WL-1)	2 4	No No Yes No	2 4	17 (PTG/30/ WL-3)
18 (PTG/25/ WL-1)	2 4	Yes No Yes Yes	2 4	18 (PTG/25/ WL-3)
18 (PTG/30/ WL-1)	2 4	No X Yes X	2 4	18 (PTG/30/ WL-3)
19 (PTG/25/ WL-1)	2 4	Yes X Yes X	2 4	19 (PTG/25/ WL-3)
19 (PTG/30/ WL-1)	2 4	Yes X Yes X	2 4	19 (PTG/30/ WL-3)
20 (PTG/25/ WL-1)	2 4	Yes X Yes X	2 4	20 (PTG/25/ WL-3)
20 (PTG/30/ WL-1)	2 4	No No Yes Yes	2 4	20 (PTG/30/ WL-3)
21 (PTG/25/ WL-1)	2 4	X X X X	2 4	21 (PTG/25/ WL-3)
21 (PTG/30/ WL-1)	2 4	X X X X	2 4	21 (PTG/30/ WL-3)

Tooth# (Rotary system/ Apical size / Needle placement)	Flow rate (ml/min)	Irrigant replacement	Flow rate (ml/min)	Tooth# (Rotary system/ Apical size / Needle placement)
22 (PTG/25/ WL-1)	2 4	Yes No Yes Yes	2 4	22 (PTG/25/ WL-3)
22 (PTG/30/ WL-1)	2 4	No No Yes Yes	2 4	22 (PTG/30/ WL-3)
23 (PTG/25/ WL-1)	2 4	Yes No Yes No	2 4	23 (PTG/25/ WL-3)
23 (PTG/30/ WL-1)	2 4	Yes No Yes No	2 4	23 (PTG/30/ WL-3)
24 (PTG/25/ WL-1)	2 4	Yes No Yes No	2 4	24 (PTG/25/ WL-3)
24 (PTG/30/ WL-1)	2 4	Yes No Yes No	2 4	24 (PTG/30/ WL-3)
25 (PTG/25/ WL-1)	2 4	Yes No Yes No	2 4	25 (PTG/25/ WL-3)
25 (PTG/30/ WL-1)	2 4	No X Yes X	2 4	25 (PTG/30/ WL-3)
26 (PTG/25/ WL-1)	2 4	Yes No Yes No	2 4	26 (PTG/25/ WL-3)
26 (PTG/30/ WL-1)	2 4	No X Yes X	2 4	26 (PTG/30/ WL-3)
27 (PTG/25/ WL-1)	2 4	Yes No Yes No	2 4	27 (PTG/25/ WL-3)
27 (PTG/30/ WL-1)	2 4	X No X Yes	2 4	27 (PTG/30/ WL-3)
28 (PTG/25/ WL-1)	2 4	Yes No Yes No	2 4	28 (PTG/25/ WL-3)
28 (PTG/30/ WL-1)	2 4	Yes No Yes Yes	2 4	28 (PTG/30/ WL-3)

X: *Samples in which apical vapor lock was not eliminated - Replacement of the contrast solution could not be measured*

Table 4.18. Predictors of replacement of the contrast solution with pure 6.0% NaOCl by positive pressure irrigation after elimination of apical vapor lock (Bivariate analyses)

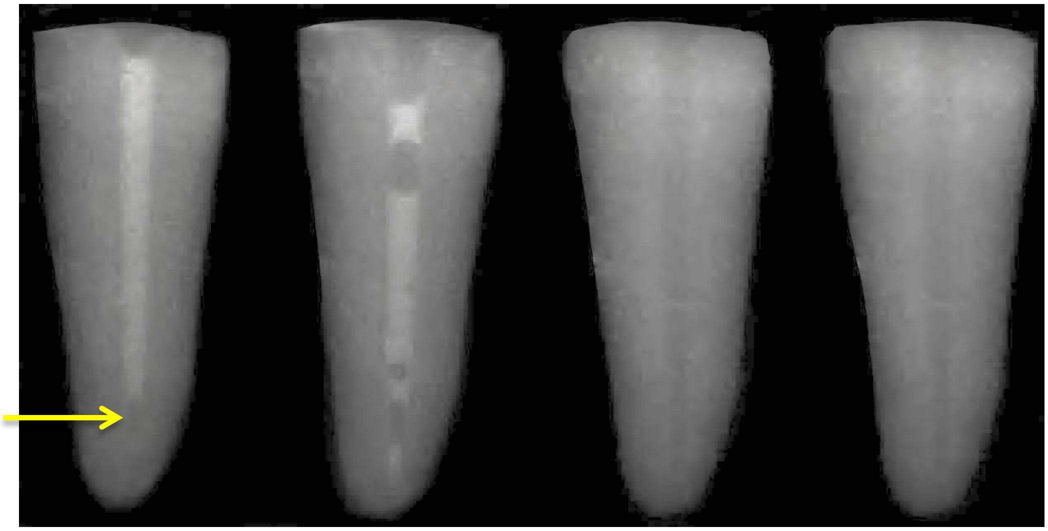
Predictors	**Replacement of contrast solution**		***p*-value #**
	No	**Yes**	
Apical size **25** ------ **30**	45/96 (46.9%) ----------------- 44/85 (51.8%)	51/96 (53.1%) ----------------- 41/85 (48.2%)	0.511
Rotary system **VB** ----- **PTG**	48/98 (49.%) ----------------- 41/82 (50.%)	50/98 (51.%) ---------------- 41/82 (50.%)	0.892
Needle placement **WL-1** ----- **WL-3**	15/90 (16.7%) ----------------- 74/91 (81.3%)	75/90 (83.3%) ---------------- 17/91 (18.7%)	0.001
Flow rate **2ml/min** -------- **4ml/min**	58/90 (64.4%) ----------------- 31/91 (34.1%)	32/90 (35.6%) ----------------- 60/91 (65.9%)	0.001

Chi-square test

Table 4.19. Predictors of replacement of the contrast solution with pure 6.0% NaOCl by positive pressure irrigation after elimination of apical vapor lock (Multivariate analysis)

Model Summary **Nagelkerke R square:** 0.562, *p*<0.001				
Predictors	**Odds ratio**	***p*-value #**	**95% CI** Lower	 Upper
Apical size (0=25, 1=30)	0.5	**0.046**	0.2	1.0
Rotary system (0= VB, 1=PTG)	0.3	**0.001**	0.1	0.4
Needle placement (0=3mm, 1=1mm)	31.1	**0.001**	12.1	84.0
Flow rate (0=2, 1=4)	6.3	**0.001**	2.7	14.9

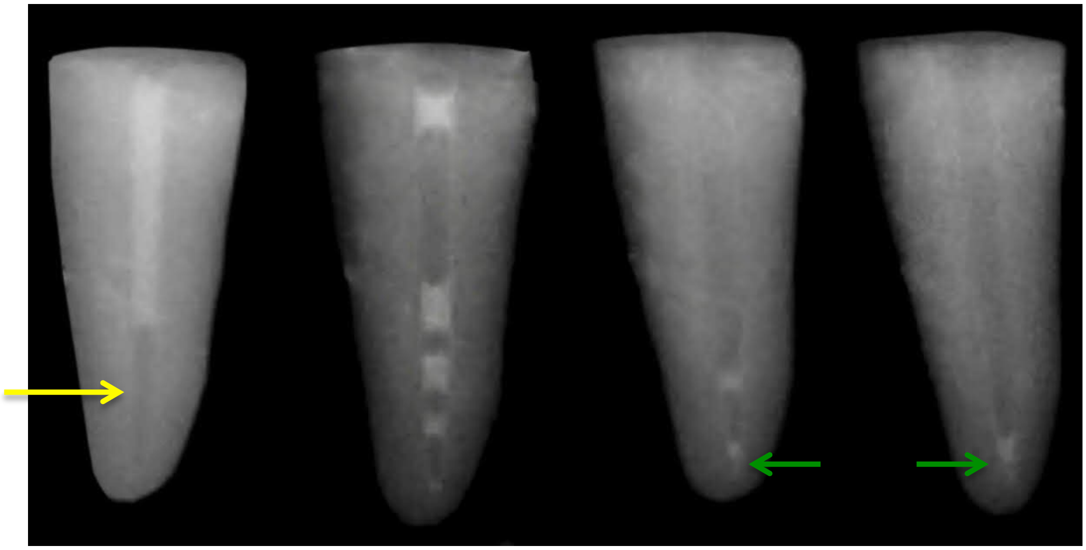
Logistic regression



A1 **A2** **A3** **A4**

Figure 4.3A. Presence and elimination apical vapor lock by manual dynamic agitation and complete replacement of the contrast solution by positive pressure irrigation in a tooth shaped with ProTaper Gold F2(25/08)

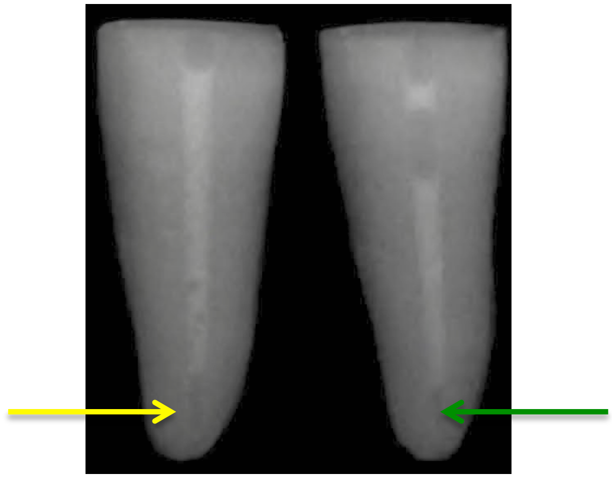
A1: Presence of AVL (*yellow arrow*) after PPI with the contrast solution at WL-1 and at 3 ml/min
A2: Elimination of AVL by MDA with 50 strokes of well-fitting gutta percha cone to WL
A3: Complete replacement of the contrast solution with pure 6.0% NaOCl by PPI at WL-1 and at 2.0 ml/min
A4: Complete replacement of the contrast solution with pure 6.0% NaOCl by PPI at WL-1 and at 4.0 ml/min



B1 **B2** **B3** **B4**

Figure 4.3B. Presence and elimination apical vapor lock by manual dynamic agitation and incomplete replacement of the contrast solution by positive pressure irrigation in a tooth shaped with ProTaper Gold F2(25/08)

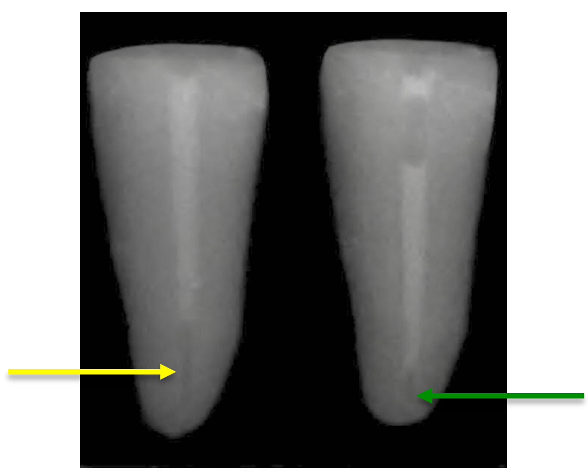
B1: Presence of AVL (*yellow arrow*) after PPI with the contrast solution at WL-3 and at 3.0 ml/min
B2: Elimination of AVL by MDA with 50 strokes of a well-fitting gutta percha cone to WL
B3: Incomplete replacement of the contrast solution (*green arrow*) with pure 6.0% NaOCl by PPI at WL-3 and at 2.0 ml/min
B4: Incomplete replacement of the contrast solution (*green arrow*) with pure 6.0% NaOCl by PPI at WL-3 and at 4.0 ml/min



C1 **C2**

Figure 4.3C. Incomplete elimination of apical vapor lock by manual dynamic agitation with 50 strokes of a well-fitting gutta percha cone to working length

C1: Presence of AVL (*yellow arrow*) after PPI with the contrast solution at WL-1 and at 3 ml/min
C2: Incomplete elimination of AVL (*green arrow*) by MDA with 50 strokes of a well-fitting gutta percha cone to WL



D1 **D2**

Figure 4.3D. Incomplete elimination of apical vapor lock by manual dynamic agitation with 50 strokes of a well-fitting gutta percha cone to working length

D1: Presence of AVL (*yellow arrow*) after PPI with the contrast solution at WL-3 and at 3 ml/min
D2: Incomplete elimination of AVL (*green arrow*) by MDA with 50 strokes of a well-fitting gutta percha cone to WL

Chapter 5: Discussion

This study is the first one to investigate the joint and independent effects of apical preparation size, rotary file system/tapering of the canal and needle insertion depth on AVL in an *ex-vivo* model simulating the clinical situation. Most of the previous irrigation studies have used open system models in which apical foramen is open to the external environment. Recently a few studies have demonstrated the overestimation of irrigation efficiency and effectiveness in open system models compared to that in closed systems, in which the apical foramen is closed to the external environment (Tay et al., 2010; Susin et al., 2010; Parente et al., 2010). The difference between the two systems can be attributed to presence of AVL at the end of a closed system (Tay et al., 2010). In the literature, various methods have been employed to simulate periapical resistance and create a closed system. These methods include: water (Boutsioukis et al., 2014), hot glue (Tay et al., 2010; Parente et al., 2010; Susin et al., 2010; Neelakantan et al., 2016), and paste-paste adhesive (Sáinz-Pardo et al., 2014). In the current study, the closed system design closely followed that of Tay et al. (2010) but with some modifications, as explained previously, to minimize accidental flow of the hot glue into the canal system. Existence of AVL can be proven indirectly by its impact on debris and smear layer removal (Tay et al., 2010; Parente et al., 2010; Susin et al., 2010). However in the present study, the attempt was to visualize the AVL radiographically by adding CsCl, a radiography contrast agent, to 6.0% NaOCl. However, CsCl can affect the physical and chemical properties of NaOCl such as dentin wettability and solvent effects. Changes in the dentin wettability property can increase or decrease likelihood of presence of AVL after PPI by increasing the surface tension of the solution (Boutsioukis et al., 2014) or by decreasing the surface tension (Giardino et al., 2012). The dentin wetting ability is defined as the surface tension of the irrigant and that of the surface to be wet. In general, surface tension is the energy required by the adhesive forces between the two surfaces to overcome the cohesive force between the like molecules on the surface of the liquid. The stronger the adhesive/inter-molecular forces or the weaker the cohesive/intra-molecular forces, the higher the liquid surface area and hence a better spread/wetting of the liquid on the surface (Giardino et al., 2012). Therefore, decreasing the surface tension of the irrigant can increase its wetting on the dentinal surface and potentially improve its penetration into the canal system. Wettability can be measured by contact angles; low contact angle indicates good wetting and high contact angle indicates poor wetting (Figure 5.1). In this study, a pilot experiment was performed to compare the contact angle of pure 6.0% NaOCl and that of the 40% contrast solution prepared by mixing 4.0 grams of CsCl in 10.0 ml of 6.0% NaOCl. This was done to minimize the bias for either presence or absence of AVL due to potential changes in the dentin wetting ability of NaOCl. The results of this pilot experiment showed no significant difference between the two contact angles (Fig 5.2). Moreover, the concave (curved in) radiographic appearance of the contrast solution (Figure 5.3) do suggest an attraction between the irrigant and the canal wall which may reject a substantial increase in the surface tension of the contrast solution. Also, in the current study, size 31-gauge close-ended double side-port needle was used to reach within 1.0 mm of the working length of the canals shaped to size 25/04. The pilot study, completed prior to the main investigation, did not show any radiographic difference between the depth of flow of the contrast solution using a 30-gauge close-ended side vented and that using a 31-gauge close-ended double side-port needle. This agrees with the CFD study that showed similar flow pattern and irrigation flow in both 30-gauge close-ended side vented and double side-port needle (Boutsioukis et al., 2010). Although size 31-gauge needles allow for a deeper penetration into the minimally shaped canals, they are more prone to blockage by NaOCl crystals which make them unsuitable for more than single use (Senia et al., 1971; Moser & Heuer, 1982). This is the reason that in the present study, the needle had to be changed after 3-4 experiments. In the current study, flow rate was not automated as pilot experiments with an automated irrigation pump through the 31-gauge needle revealed inaccurate and inconsistent flow rates. In non-automated settings, flow rate depends on operator's strength, length of the fingers and patience, barrel volume and needle gauge size (Boutsioukis et al., 2007). Injection through needles with smaller inner diameter especially those with close ends, requires greater force on the plunger to produce the intra-barrel pressure needed to achieve/maintain desired flow rate (Moser and Heuer, 1982; Boutsioukis et al., 2007). The force required also depends on the plunger surface area which in turn correlates with the barrel capacity. Since pressure [P] is defined as force [F] applied over a surface area [A] *P: F/A* (Pashley et al., 1981), the larger the surface area of the plunger, the higher the force needed to generate sufficient intra-barrel pressure for maintenance of a certain flow rate (Boutsioukis et al., 2007). In the current study, a 3.0 ml syringe was used because its smaller plunger surface area allowed the operator to maintain a consistent, precise flow rate through the 31-gauge needle without experiencing muscle fatigue although the syringe required frequent re-fill.

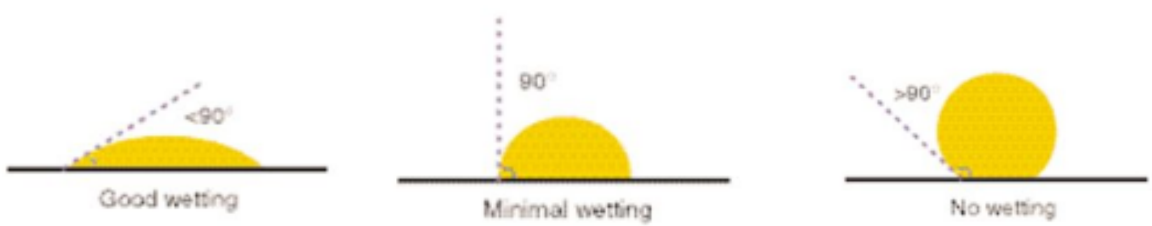
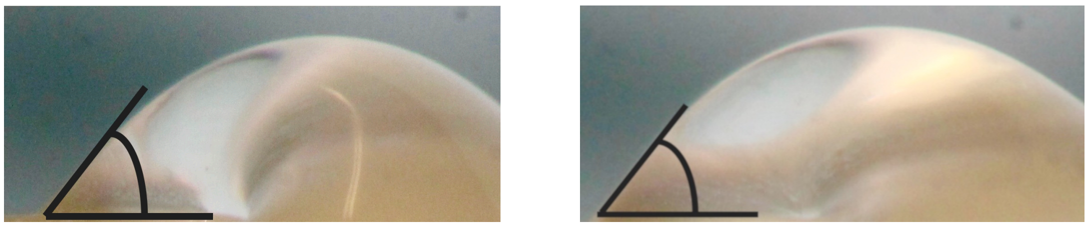


Figure 5.1. Relationship between the contact angle and the wettability of a solid surface



A B

Figure 5.2. No difference in the contact angle between A) pure 6.0% NaOCl and B) 40.0% contrast solution (NaOCl & CsCl)

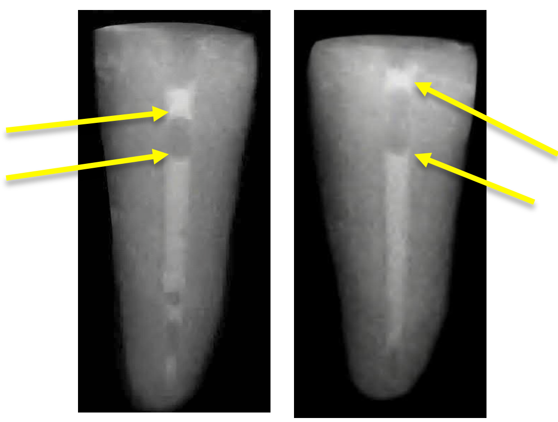


Figure 5.3. Concave (curved in) radiographic appearance of the contrast solution after PPI (*yellow arrow*)

In the current study, AVL was detected in 92.0% of the samples after PPI with the contrast solution. Our finding closely agrees with presence of AVL in 100% of the teeth in a recent *ex-vivo* experiment (Agarwal et al., 2017). However, another *ex-vivo* study showed the presence of AVL in only 70.0% of samples when irrigation with a contrast mixture was performed at an unknown flow rate through a 30-gauge close-ended side vented needle placed at WL-2 (Sainz-Padro et al., 2014). A combined *in-vitro* and CFD study by Boutsioukis et al. (2014) demonstrated the presence of AVL in 62.5% of the samples when the flow rate was set at 2.0 ml/min-15.6 ml/min (0.033 ml/s-0.26 ml/s) and irrigation was performed through a 30-gauge close-ended needle that was inserted at WL-1 and WL-3 (Boutsioukis et al., 2014). The authors reported that the presence of AVL after PPI was more frequently associated with the low flow rates. Therefore, at the flow rate of 2.0 ml/min (~0.033ml/s), AVL was present in all the samples regardless of the root canal size (35/04 or 50/04) and needle insertion depth (WL-1 or WL-3) (Boutsioukis et al., 2014). In the present study, needle insertion depth (WL-1 and WL-3) and apical size (25 and 30) also did not influence the presence of AVL when PPI was performed at the flow rate of 3.0 ml/min (0.05 ml/s). In the study by Boutsioukis et al. (2014), authors reported that use of resin blocks with hydrophobic surfaces can increase the contact angle between the canal wall and NaOCl and hence heighten the likelihood of the presence of AVL (Boutsioukis et al., 2014). However, using the same resinous model, the authors concluded that at higher flow rates of 5.0 ml/min (~0.083 ml/s) and 10.0 ml/min (~0.166 ml/s), AVL was infrequent and at the flow rate of 15.6 ml/min(0.26 ml/s), no AVL was present (Boutsioukis et al., 2014). Therefore, presence of AVL after PPI could be affected by the flow rate. This finding is also supported by the results of the current study. In the present study, AVL was present in 92.0% of the samples when irrigation was performed at the flow rate of 3.0 ml/min (0.05 ml/s) as compared to the presence of AVL in 100.0% of the samples when irrigation was performed at the flow rate of 2.0 ml/min (~0.033ml/s) in the study by Boutsioukis et al. (2014).

Moreover, in the current study, it was observed that AVL is more likely to be present after PPI in teeth that are shaped with PTG rotary file system when compared to those teeth that are shaped with VB if controlled for both apical preparation size and needle insertion depths. In another study, AVL was present in 100% of the samples that were shaped with PTG F4- 40/06 (Agarwal et al., 2017). Whereas in teeth that were shaped with fixed 06 and 04 taper rotary files, AVL was present in 70.0% (Sainz-Padro et al., 2014) and 62.5% (Boutsioukis et al., 2014) of the samples respectively. These findings may be partly explained by the differences in the tapering of both rotary file systems. VB and PTG rotary file systems differ in their tapering; Vortex Blue used in this study has a fixed 04 taper, whereas PTG has a variable taper with a larger taper in the apical 3.0 mm, 08 for F2 and 09 for F3. Fixed taper design may provide continuous coronal space around the needle for the backflow of any turbulence that is generated during PPI. Coronal escape of the turbulent flow allows for apical penetration of the irrigant with the laminar flow (Bronnec et al., 2010). Therefore, better irrigant penetration during PPI can potentially remove the AVL in teeth that are shaped with fixed taper rotary files compare to those that are shaped with PTG.

The present study investigated the effects of numbers of strokes of a well-fitting gutta percha cone to WL on AVL elimination in a pilot experiment. The pilot experiment was performed to determine an effective number of strokes that could be used to further investigate the effects of other predictors on the efficacy of MDA. There are numerous techniques and delivery devices to improve the irrigant flow and distribution to the full length of the canal system (Gu et al., 2009). MDA has been introduced as one of the cost effective and simple techniques to improve the irrigation within the canal system. According to literature, studies on MDA have investigated different numbers of strokes with either a well-fitting gutta percha cone or a K File. These studies included: 100 strokes in 1.0 minute with well-fitting gutta percha cone (Parente el al., 2010; Susin et al., 2010; Neelakantan et al., 2016), 100 strokes with a well-fitting gutta percha cone (Huang et al., 2008; McGill et. al., 2008), 15 strokes in 10.0 seconds with a well-fitting gutta percha cone (Boutsioukis et al., 2014), 3 strokes with a well-fitting gutta percha cone (Bronnec et al., 2010), and 1.0 minute of strokes with a size 15 K file (Agarwal et al., 2017). The setting with 100 strokes may be laborious for clinicians; therefore, in this study, the attempt was to examine the effectiveness of lower numbers of strokes. The findings demonstrated that there is a significant difference between the efficacy of 50 strokes of a well-fitting gutta percha cone and that of either 40 or 10 strokes. The number of strokes affected the elimination of AVL with or without considering other modalities such as the apical preparation size, the rotary file system and the needle insertion depth. Although 50 strokes might seem laborious, in this study, it was performed within 35 seconds (86 strokes/min). At such frequency, there was no extrusion of contrast solution from the closed system that could be detected radiographically in any of the samples. This finding was similar to the report of Parente et al. (2010), but contradicts the results of Boutsioukis et al. (2014) who showed that MDA with a flow rate of 1.5 strokes/second (90.0 strokes/min) causes significant extrusion of irrigant into the simulated periapical tissue (water filled vials). Such difference may be explained by the different back pressure resistance offered by water and hot glue.

For the first time, the present study attempted to investigate the joint effects of several predictors such as the apical preparation size, the type of rotary file system and the needle insertion depth on the efficacy of apical vapor lock elimination by MDA. According to the literature, previous studies on the effectiveness of MDA included teeth with larger apical shaping and also some studies chose larger tapering: fixed taper 40/06 (Parente et al., 2010), fixed taper 35/04 (Susin et al., 2010), variable taper PTG F2-25/08 (Neelakantan et al., 2016) and variable taper PTG F4-40/06 (Agarwal et al., 2017). In the current study, the experimental teeth were shaped to smaller apical preparation sizes with fixed (VB-25/04 and 30/04) and variable taper rotary file systems (PTG F2-25/08 and F3-30/09). The results showed that AVL was eliminated in 81.6% of the samples. This finding is higher than the results of a similar *ex-vivo* study that directly measured the elimination of AVL by MDA via radiographic means, where AVL elimination by MDA was only in 50.0% (10/20) of the samples (Agarwal et al., 2017). The difference between the results of the current study and that of the study by Agarwal et al. (2017) could be attributed to their smaller sample size and also using a size 15 K file at WL-1 for MDA instead of using a well-fitting gutta percha cone to WL. It was suggested that rapid strokes with a well-fitting gutta percha cone that adapts closely to the canal walls can generate high intra-canal pressure changes that moves the irrigant apically and to the un-instrumented canal surfaces (McGill et al., 2008). Therefore, agitation with a size 15 K file that does not adapt the canal walls closely may not produce sufficient intra-canal pressure needed for successful apical movement of the irrigant.

In the current study, the bivariate analyses indicated that there were no differences between the apical preparation size 25 and 30, the rotary file system PTG and VB and the needle insertion depth at WL-1 and WL-3 with respect to elimination of AVL. However, the multivariate analysis showed that the type of the rotary file system was a significant predictor of the AVL elimination. Teeth that were shaped with PTG as compared to the ones shaped with VB had a higher chance of having the formed AVL eliminated. The variable tapering of PTG with deep apical shaping may address the canal walls more effectively than the VB with fixed 04 taper. Hence, the well-fitting PTG gutta percha cone may leave less space between the canal wall and the cone when compared to that of VB and canals walls. This avaiable space may allow backflow of the irrigant during MDA and reduce its apical movement. Therefore, shaping with PTG leaves less space between the canal wall and the cone and MDA causes irrigant to be pushed apically more effectively for the better displacement of AVL when compared to shaping with VB. The results for "pilot experiment question #3" showed that shaping with PTG decreases the odds of AVL elimination when different numbers of strokes were tested. However, in this section of the study, when a fixed number of 50 strokes was used for all the samples, shaping with PTG increased the likelihood of AVL elimination. Thus, these results may suggest that the lower number of strokes (10 and 40) adversely influence AVL elimination in teeth that are shaped with PTG. An increase in the number of strokes favors AVL elimination in teeth that are shaped with PTG in comparison to teeth that are shaped with VB.

It is important to caution that elimination of AVL does not necessarily indicate the cleanness of the canal system. The limitation of the current study is that the effectiveness of MDA on canal debridement was not investigated. However, canal debridement by MDA has been the focus of few previous studies. Huang et al. (2008) examined the influence of different factors including MDA with gutta percha cone on residual collagen on the canal walls. Although, that study model presented an open system, MDA with 100 strokes with a well-fitting gutta percha cone showed to be more effective in removing the stained collagen than PPI. Moreover, it was shown that larger apical shaping and tapering increased the efficacy of MDA in the removal of stained collagen (Huang et al., 2008). In another study, SEM analysis showed that 100 strokes of MDA with a well-fitting gutta percha cone is less effective in removing canal debris and smear layer in a closed system than in an open system (Parente et al., 2010). MDA (100 strokes per min) showed to perform similar to EndoVac (apical negative pressure system) in cleaning the canal debris in an *ex-vivo* experiment but was less effective in cleaning the isthmi (Susin et al., 2010). In another study, MDA demonstrated to be more effective than passive ultrasonic irrigation in removing the remaining pulpal tissue in the isthmi at 1.0 mm and 3.0 mm from the apex (Neelakantan et al., 2016). These studies do suggest that MDA can increase the irrigant flow to the apical third by potentially displacing the AVL as was demonstrated in the current study. However, SEM and light microscopy analyses indicate that although MDA might be an effective technique in removing the AVL, debris and smear layer can potentially remain as they don't have the space around the cone to exit coronally (Parente et al., 2010). Therefore, in the third part of this study, the aim was to investigate irrigant penetration by PPI after elimination of AVL in order to improve canal debridement after MDA.

Continued replacement and replenishment of the irrigant is imperative in maintaining the disinfectant (Harrison & Hand, 1981) and solvent (Moorere & Wesselink, 1982) properties of the irrigant. Numerous studies tested several factors that can contribute to efficacy of root canal irrigation. These factors include: apical preparation size (Usman et al., 2004, Hsieh et al., 2007, Huang et al., 2008, Boutsioukis et al., 2014) and taper (Huang et al., 2008), distance of the irrigation needle to the apex (Sedgley et al., 2005, Hsieh et al., 2007, Bronnec et al., 2010, Boutsioukis et al., 2014), irrigation volume (Baker et al., 1975, Moser & Heuer, 1982, Sedgley et al., 2004, Huang et al., 2008) and dimension of the irrigating needles (Hsieh et al., 2007).

The current study showed that there is a significant difference between different needle insertion depths (1.0 mm versus 3.0 mm) and flow rates (2.0 ml/min versus 4.0 ml/min) with respect to apical penetration of pure 6.0% NaOCl and hence replacement of the contrast solution. However, all four predictors (apical preparation size, rotary file system, needle insertion depth and flow rate) influenced the irrigation penetration in an independent manner, i.e. when it was controlled for the other three factors. In the present study, maximum flow rate was 4.0 ml/min (~0.067 ml/s) because it has been shown that clearance zone/stagnation plane beyond the needle tip reaches its maximum at the flow rate of 4.0 ml/min and does not extend further at higher flow rates (Park et al., 2013). In the current study, the odds of the contrast solution replacement increased in teeth that were shaped with VB as compared to teeth that were shaped with PTG. VB has a fixed taper, whereas PTG has a variable taper with larger tapering in the apical 3.0 mm. Fixed taper design may provide continuous coronal space around the needle to allow backflow of any turbulence that is generated during PPI. This can improve apical movement of the irrigant with laminar flow as the turbulent irrigant escapes coronally (Bronnec et al., 2010). Therefore, shaping with fixed taper rotary files can improve the apical penetration of 6.0% NaOCl by PPI in order to replace the contrast solution after elimination of AVL. Also, in the present study, smaller ISO apical size (25 versus 30) increased the odds of contrast solution replacement after elimination of apical vapor lock. This finding disagrees with the accepted notion that larger apical preparation increases irrigation penetration (Ram, 1977; Hsieh et al., 2007; Gulabivala et al., 2008, Boutsioukis et al., 2014). In a thermal image analysis study, it was shown that needle diameter as well as needle insertion depth and apical preparation size can affect the successful root canal irrigation into the apex (Hsieh et al., 2007). The authors of that study concluded that the larger apical preparation size was needed for two reasons: 1) for closer placement of the needle to the apex and 2) for successful irrigation when using a smaller gauge needle. According to their results, needles of smaller gauge (with larger inner diameter) can affect the fluid flow adversely (Hsieh et al., 2007). Therefore, larger gauge needles such as the 31-gauge used in the current study allowed a closer positioning to the apex and also its smaller diameter may have affected the fluid flow positively for the successful apical penetration of the irrigant. In a historical study by Ram (1977), apical preparation size was shown to be an important factor for irrigation renewal after the apical third of the canal was filled with radiopaque solution. In that study, when the open-ended needle was placed in the coronal third, irrigation renewal was incomplete in canals shaped to less than ISO size 40 although much more volume was used in canals shaped to ISO size 25 (Ram, 1977). In the present study, both apical ISO sizes 25 and 30 allowed placement of 31-gauge needle at WL-1 but seemingly larger apical preparation decreased irrigation penetration. This difference may be explained by the non-laminar/turbulent flow of irrigant in a closed end system as shown in CFD models by Boutsioukis et al., (2009). The turbulent flow is generated as soon as the irrigant contacts the irregular walls of the root canal system. Such turbulence causes a backflow which can complicate the apical penetration of the irrigant form the needle (Boutsioukis et al., 2009). Moreover, bigger apical preparation can cause formation of more turbulence (Hsieh et al., 2007). Therefore, apical preparation to ISO size 30 might decrease apical penetration of irrigant due to more turbulence formation than preparation with ISO size 25. A different study investigated irrigation penetration in curved canals after elimination of AVL by manually agitating a hypaque solution to the apical third of the canals (Bronnec et al., 2010). The authors of that study concluded the dominance of needle insertion depth (3.0 mm & 6.0 mm from WL) and influence of apical tapering (0.07, 0.08 & 0.09) and volume (1.0 ml & 3.0 ml) at a constant flow rate of 12.0 ml/min on irrigation penetration and replacement (Bronnec et al., 2010). Similar to that study, the results of the current study show the dominance of needle insertion depth in the replacement of the contrast solution regardless of the flow rates (2.0 ml/min & 4.0 ml/min). In the present study, when needle was placed at WL-1, both flow rates of 2.0 ml/min and 4.0 ml/min were effective in replacing the contrast solution completely. However, when needle was placed at WL-3, the replacement of the contrast solution was incomplete even at 4.0 ml/min. This finding may support that irrigant flow is limited to 1.0 mm beyond the tip of a close-ended side vented needle at the flow rates: ~2 ml/ min-15.6 ml/min (Boutsioukis et al., 2009) when there is no AVL present. Also the difference between the insertion depths can be explained through another CFD study by Boutsioukis et al. (2010). They showed that vertical vortices (structures where flow is rotating) form apical to the side vented needle. As the needle position furthers form the WL, the number of these vortices increase; These vortices can cause some irrigant replacement but as the number increases, there is a delay in the irrigant replacement (Boutsioukis et al., 2010).

Therefore, the results of this section of the study show that when AVL is eliminated, complete apical penetration of irrigant is probable and its probability is influenced by the needle insertion depth and the flow rate. Future research is needed to investigate the effects of different insertion depths and their minimum flow rates that can result in successful irrigation replacement after AVL has been eliminated.

Chapter 6: Conclusion

Within the limitations of this study, shaping with ProTaper Gold rotary files has a joint effect on the formation and elimination of apical vapor lock. Replacement of the contrast solution with sodium hypochlorite was affected by the independent effects of needle insertion depth and flow rate and the joint effect of needle insertion depth, flow rate, rotary file system and apical size preparation.

The overall findings of this study suggest:

- Apical vapor lock is highly likley to be present after positive pressure irrigation into a dry canal system.
- Manual dynamic agitation with 50 rapid strokes of a well-fitting gutta percha cone to working length is effective for the removal of apical vapor lock.
- When apical vapor lock is eliminated by manual dynamic agitation, positive pressure irrigation can be performed subsequently to improve canal debridement by mechanical flushing of the remaining debris and replacement of consumed NaOCl with fresh irrigant for chemical removal of organic debris and bacteria.

References

1. Abou-Rass, M., & Piccinino, M. V. (1982). **The effectiveness of four clinical irrigation methods on the removal of root canal debris**. Oral surgery, oral medicine, and oral pathology, 54(3), 323–328.

2. Agarwal, A., Deore, R. B., Rudagi, K., Nanda, Z., Baig, M. O., & Fareez, M. A. (2017). **Evaluation of apical vapor lock formation and comparative evaluation of its elimination using three different techniques: An in vitro study**. Journal of Contemporary Dental Practice, 18(9), 790–794.

3. Baker, N. a, Eleazer, P. D., Averbach, R. E., & Seltzer, S. (1975). **Scanning electron microscopic study of the efficacy of various irrigating solutions**. Journal of Endodontics, 1, 127–135.

4. Baumgartner, JC., Mader, CL. (1987). **A scanning electron microscopic evaluation of four root canal irrigation regimens**. Journal of Endodontics, 13,147-157.

5. Boutsioukis, C., Kastrinakis, E., Lambrianidis, T., Verhaagen, B., Versluis, M., & van der Sluis, L. W. M. (2014). **Formation and removal of apical vapor lock during syringe irrigation: A combined experimental and Computational Fluid Dynamics approach**. International Endodontic Journal, 47(2), 191–201.

6. Boutsioukis, C., Psimma, Z., & Van der Sluis, L. W. M. (2013). **Factors affecting irrigant extrusion during root canal irrigation: A systematic review**. International Endodontic Journal, 46(7), 599–618.

7. Boutsioukis, C., Verhaagen, B., Versluis, M., Kastrinakis, E., Wesselink, P. R., & van der Sluis, L. W. M. (2010). **Evaluation of irrigant flow in the root canal using different needle types by an unsteady computational fluid dynamics model**. Journal of Endodontics, 36(5), 875–879.

8. Boutsioukis, C., Lambrianidis, T., & Kastrinakis, E. (2009). **Irrigant flow within a prepared root canal using various flow rates: A Computational Fluid Dynamics study**. International Endodontic Journal, 42(2), 144–155.

9. Boutsioukis, C., Lambrianidis, T., Kastrinakis, E., & Bekiaroglou, P. (2007). **Measurement of pressure and flow rates during irrigation of a root canal *ex vivo* with three endodontic needles**. International Endodontic Journal, 40(7), 504–513.

10. Bronnec, F., Bouillaguet, S., & Machtou, P. (2010). ***Ex vivo* assessment of irrigant penetration and renewal during the final irrigation regimen**. International Endodontic Journal, 43(8), 663–672.

11. Byström, A., & Sundqvist, G. (1983). **Bacteriologic evaluation of the effect of 0.5 percent sodium hypochlorite in endodontic therapy**. Oral surgery, oral medicine, and oral pathology, 55(3), 307–312.

12. Chow, T. W. (1983). **Mechanical effectiveness of root canal irrigation**. Journal of Endodontics, 9(11), 475–479.

13. Dalton, B. C., Ørstavik, D., Phillips, C., Pettiette, M., & Trope, M. (1998). **Bacterial reduction with nickel-titanium rotary instrumentation**. Journal of Endodontics, 24(11), 763–767.

14. Druttman, A. C., & Stock, C. J. (1989). **An in vitro comparison of ultrasonic and conventional methods of irrigant replacement**. International Endodontic Journal, 22(4), 174–178.

15. Endal, U., Shen, Y., Knut, A., Gao, Y., & Haapasalo, M. (2011). **A high-resolution computed tomographic study of changes in root canal isthmus area by instrumentation and root filling**. Journal of Endodontics, 37(2), 223–227.

16. Gao, Y., Haapasalo, M., Shen, Y., Wu, H., Li, B., Ruse, N. D., & Zhou, X. (2009). **Development and validation of a three-dimensional computational fluid dynamics model of root canal irrigation**. Journal of Endodontics, 35(9), 1282–1287.

17. Giardino, L., Morra, M., Becce, C., Pappen, F. G., Mohammadi, Z., & Palazzi, F. (2012). **Comparative wettability of different sodium hypochlorite solutions**. Giornale Italiano Di Endodonzia, 26(2), 57–62.

18. Gu, L. sha, Kim, J. R., Ling, J., Choi, K. K., Pashley, D. H., & Tay, F. R. (2009). **Review of Contemporary Irrigant Agitation Techniques and Devices**. Journal of Endodontics, 35(6), 791–804.

19. Gulabivala, K., Ng, Y.-L., Gilbertson, M., & Eames, I. (2010). **The fluid mechanics of root canal irrigation**. Physiological measurement, 31(12), R49–84.

20. Gulabivala, K., Patel, B., & Evans, G. (2005). **Effects of mechanical and chemical procedures on root canal surfaces**. Endodontic Topics. 10(1), 103-122.

21. Hsieh, Y. D., Gau, C. H., Kung Wu, S. F., Shen, E. C., Hsu, P. W., & Fu, E. (2007). **Dynamic recording of irrigating fluid distribution in root canals using thermal image analysis**. International Endodontic Journal, 40(1), 11–17.

22. Harrison JW, Hand RE. (1981). **The effect of dilution and organic matter on the anti-bacterial property of 5.25% sodium hypochlorite**. Journal of Endodontics. 7(3),128-32.

23. Huang, T. Y., Gulabivala, K., & Ng, Y. L. (2008). **A bio-molecular film *ex-vivo* model to evaluate the influence of canal dimensions and irrigation variables on the efficacy of irrigation**. International Endodontic Journal. 41(1), 60-71.

24. Jiang, L.-M., Verhaagen, B., Versluis, M., & van der Sluis, L. W. M. (2010). **Evaluation of a sonic device designed to activate irrigant in the root canal**. Journal of Endodontics, 36(1), 143–146.

25. Kahn, F. H., Rosenberg, P. A., & Gliksberg, J. (1995). **An in vitro evaluation of the irrigating characteristics of ultrasonic and subsonic handpieces and irrigating needles and probes**. Journal of Endodontics, 21(5), 277–280.

26. Kakehashi, S., Stanley, H. R., & Fitzgerald R. J. (1965). **The effects of surgical exposures of dental pulps in germ-free and conventional laboratory rats**. Oral Surgery, Oral Medicine, and Oral Pathology, 20, 340–349.

27. Marshall, F., & Rosen, S. (1970). **The bactericidal efficiency of sodium hypochlorite as an endodontic irrigant**. Oral Surgery. 29(4), 613-619.

28. McGill, S., Gulabivala, K., Mordan, N., & Ng, Y. L. (2008). **The efficacy of dynamic irrigation using a commercially available system (RinsEndo®) determined by removal of a collagen "bio-molecular film" from an *ex vivo* model**. International Endodontic Journal, 41(7), 602–608.

29. Metzger, Z., Zary, R., Cohen, R., Teperovich, E., & Paqué, F. (2010). **The quality of root canal preparation and root canal obturation in canals treated with rotary versus self adjusting files: a three-dimensional micro-computed tomographic study**. Journal of Endodontics, 36(9), 1569–1573.

30. Möller AJ. (1966). **Microbiological examination of root canals and peri- apical tissues of human teeth methodological studies**. Odontol Tidskr, 74, 1–380.

31. Moorer, W.R., & Wesselink, P.R. (1982**). Factors promoting the tissue dissolving capability of sodium hypochlorite**. Journal of Endodontics, 15(4), 187-19.

32. Moser, J. B., & Heuer, M. A. (1982). **Forces and efficacy in endodontic irrigation systems**. Oral Surgery, Oral Medicine, Oral Pathology, 53(4), 425–428.

33. Nair, P., Cano, V., & Vera, J. (2005). **Microbial status of apical root canal system of human mandibular first molars with primary apical periodontitis**. Oral Surgery. 99 (2), 231-252.

34. Naenni, N., Thoma, K., & Zehnder, M. (2004). **Soft Tissue Dissolution Capacity of Currently Used and Potential Endodontic Irrigants**. Journal of Endodontics, 30(11), 785–787.

35. Neelakantan, P., Devaraj, S., & Jagannathan, N. (2016). **Histologic Assessment of Debridement of the Root Canal Isthmus of Mandibular Molars by Irrigant Activation Techniques *Ex Vivo***. Journal of Endodontics, 42(8), 1268–1272.

36. Ørstavik, D. & Pitt Ford, T.R (2008). **Essential endodontology: prevention and treatment of apical periodontitis**, 2nd edn, Blackwell Munksgaard, Ames, Iowa;Oxford, UK.

37. Paqué, F., Balmer, M., Attin, T., & Peters, O. A. (2010). **Preparation of oval-shaped root canals in mandibular molars using nickel-titanium rotary instruments: a microcomputed tomography study**. Journal of Endodontics, 36(4), 703–707.

38. Parente, J. M., Loushine, R. J., Susin, L., Gu, L., Looney, S. W., Weller, R. N. Tay, F. R. (2010). **Root canal debridement using manual dynamic agitation or the EndoVac for final irrigation in a closed system and an open system.** International Endodontic Journal, 43(11), 1001–1012.

39. Park E, Shen Y, Khakpour M, Haapasalo M.(2013). **Apical pressure and extent of irrigant flow beyond the needle tip during positive-pressure irrigation in an in vitro root canal model**. Journal of Endodontic, 39(4), 511-5.

40. Pashley, E. L., Nelson, R., & Pashley, D. H. (1981). **Pressures Created by Dental Injections**. Journal of Dental Research, 60(10), 1742–1748.

41. Pesse, A. V., Warrier, G. R., & Dhir, V. K. (2005). **An experimental study of the gas entrapment process in closed-end microchannels**. International Journal of Heat and Mass Transfer, 48(25–26), 5150–5165.

42. Ram, Z. (1977). **Effectiveness of root canal irrigation**. Oral Surgery, Oral Medicine, and Oral Pathology, 44(2), 306–312.

43. Sáinz-Pardo, M., Estevez, R., de Pablo, Ó. V., Rossi-Fedele, G., & Cisneros, R. (2014). **Root canal penetration of a sodium hypochlorite mixture using sonic or ultrasonic activation**. Brazilian Dental Journal, 25(6), 489–493.

44. Salzgeber, R. M., & Brilliant, J. D. (1977). **An in vivo evaluation of the penetration of an irrigating solution in root canals.** Journal of Endodontics, 3(10), 394–398.

45. Sedgley, C. (2004). **Root canal irrigation--a historical perspective**. Journal of the history of dentistry, 52(2), 61–65.

46. Sedgley, C. M., Nagel, A. C., Hall, D., & Applegate, B. (2005). **Influence of irrigant needle depth in removing bioluminescent bacteria inoculated into instrumented root canals using real-time imaging in vitro**. International Endodontic Journal, 38(2), 97–104.

47. Senia, E. S., Marshall, F. J., & Rosen, S. (1971). **The solvent action of sodium hypochlorite on pulp tissue of extracted teeth**. Oral Surgery, Oral Medicine and Oral Pathology, 1971.pdf. Oral Surgery, (Dc).

48. Shen, Y., Gao, Y., Qian, W., Ruse, N. D., Zhou, X., Wu, H., & Haapasalo, M. (2010). **Three-dimensional numeric simulation of root canal irrigant flow with different irrigation needles**. Journal of Endodontics, 36(5), 884–889.

49. Siqueira, J., J F, Rôças, I.N., Ricucci, D. & Hülsmann, M. (2014). **Causes and management of post-treatment apical periodontitis.** British Dental Journal, 216(6), 305.

50. Siqueira, J. F., & Rôças, I. N. (2008). **Clinical implications and microbiology of bacterial persistence after treatment procedures**. Journal of Endodontics, 34(11), 1291–1301.

51. Stojicic, S., Shen, Y., & Qian, W. (2011). **Antibacterial and smear layer removal ability of a novel irrigant, QMiX**. International Endodontic Journal, 45(4), 363-371.

52. Sundqvist G. (1976). **Bacteriological studies of necrotic dental pulps.** Umeå University Odontological Dissertations No. 7.

53. Susin, L., Liu, Y., Yoon, J. C., Parente, J. M., Loushine, R. J., Ricucci, D., Tay, F. R. (2010). **Canal and isthmus debridement efficacies of two irrigant agitation techniques in a closed system**. International Endodontic Journal, 43(12), 1077–1090.

54. Tay, F. R., Gu, L. sha, Schoeffel, G. J., Wimmer, C., Susin, L., Zhang, K., Pashley, D. H. (2010). **Effect of vapor lock on root canal debridement by using a side-vented needle for positive-pressure irrigant delivery**. Journal of Endodontics, 36(4), 745–750.

55. Usman, N., Baumgartner, J. C., & Marshall, J. G. (2004). **Influence of instrument size on root canal debridement**. Journal of Endodontics, 30(2), 110–112.

56. Vertucci, F. (1984). **Root canal anatomy of the human permanent teeth**. Oral Surgery, Oral Medicine, Oral Pathology. 58(5), 589-599.

57. Walia, H., & Brantley, W. (1988). **An initial investigation of the bending and torsional-properties of Nitinol root canal files**. Journal of Endodontics. 14(7), 346-351.