APICAL VAPOR LOCK EFFECT IN CONSERVATIVE NI-TI INSTRUMENTATION

USING V-TAPER ROTARY SYSTEM

by

Veselin Trifonov

DDS, University of Toronto, 2017

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Craniofacial Science)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

February 2020

© Veselin Trifonov, 2020
The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, a thesis entitled:

Apical vapor lock effect in conservative Ni-Ti instrumentation using V-taper rotary system

submitted by Veselin Trifonov in partial fulfillment of the requirements for the degree of Master of Science in Craniofacial Science

Examiner Committee:

Dr. Ya Shen  
Supervisor

Dr. Markus Haapasalo  
Supervisory Committee Member

Dr. Ahmed Hieawy  
Supervisory Committee Member

Dr. Vincent Lee  
External Examiner
Abstract

Aim: The presence of apical vapor lock during irrigation has been shown to have a negative impact on debris and smear layer removal. The aim of this study was first, to compare apical vapor lock formation during positive pressure syringe irrigation following conventional, ProTaper Gold and conservative, V-taper nickel-titanium instrumentation. The second aim was to evaluate effectiveness of apical vapor lock elimination by sonic, ultrasonic and manual dynamic agitation, once established.

Methods: Thirty-six single rooted teeth were instrumented with either ProTaper Gold F2 (25/0.08) or V-taper (25/0.06). In the first part of the study, incidence of apical vapor lock formation was evaluated radiographically following irrigation with sodium hypochlorite and cesium chloride (contrast agent). In the second part, apical vapor lock elimination was evaluated using manual dynamic agitation with 50 strokes of a well-fitting gutta-percha cone. Sonic agitation was performed with the EndoActivator, while ultrasonic agitation was carried out using a piezoelectric unit and a ISO size 15 U-File.

Results: Following positive pressure irrigation, apical vapor lock was detected radiographically in 75.0% of total cases, specifically 72.2% and 77.8% of samples instrumented with V-taper and ProTaper Gold, respectively. Manual dynamic agitation eliminated apical vapor lock in 92% of samples, significantly more effective when compared to sonic and ultrasonic agitation.

Conclusion: Apical vapor lock was equally detected after conservative and conventional rotary instrumentation using V-taper and ProTaper Gold, respectively. Manual dynamic agitation was effective at eliminating apical vapor lock.
Lay Summary

The disinfection process of root canal treatment is complicated by the extraordinary complexity of the root canal system. The root canal consists of various types of channels that are connected to the main canal. The use of instruments alone is inadequate at targeting all the various regions in a root canal system. Clinicians depend on chemical solutions to facilitate the disinfection process. A physical phenomenon that occurs during delivery of solutions is the production of apical vapor lock. It is the formation of air bubbles in a closed channel when a solution is delivered towards the end of that channel. The root is surrounded by bone and therefore acts as a closed system as well. The formation of apical vapor lock has negative implications when it comes to disinfecting the root canal system by impeding bacterial removal. Elimination of apical vapor lock maybe achieved by manual dynamic agitation, sonic or ultrasonic agitation.
Preface

This study was approved by the University of British Columbia Clinical Research Ethics Board (Certificate H15-02793)

The relative contribution of the collaborators in this project were:

Dr. Veselin Trifonov: Research, collection and analysis of data. Writing of the thesis.

Dr. Ya Shen: Analysis of the research data. Editing of the thesis.

Dr. Markus Haapasalo: Editing of the thesis.

Dr. Ahmed Hieawy: Editing of thesis.
Table of Contents

Abstract ........................................................................................................................................ iii
Lay Summary ................................................................................................................................ iv
Preface ........................................................................................................................................... v
Table of Contents .......................................................................................................................... vi
List of Tables ................................................................................................................................... viii
List of Figures ..................................................................................................................................... ix
List of Abbreviations ...................................................................................................................... x
Acknowledgements ........................................................................................................................ xi
Dedication ......................................................................................................................................... xii

Chapter 1: Introduction .................................................................................................................. 1
  1.1 Objective in Endodontics ........................................................................................................ 1
  1.2 Mechanical instrumentation ................................................................................................. 1
  1.3 Irrigants .................................................................................................................................... 3
    1.3.1 Sodium hypochlorite (NaOCl) ....................................................................................... 3
    1.3.2 Organic tissue dissolution ............................................................................................ 4
    1.3.3 Antimicrobial ................................................................................................................ 5
  1.4 Canal taper influence on irrigation ....................................................................................... 6
  1.5 Agitation of irrigants ............................................................................................................. 7
    1.5.1 Manual dynamic agitation ............................................................................................ 9
    1.5.2 Sonic agitation .............................................................................................................. 9
    1.5.3 Ultrasonic agitation .................................................................................................... 10
List of Tables

Table 4.1. Presence of apical vapor lock following positive pressure irrigation 1 mm short of the working length in roots instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08 (Chi-square test)........................................................................................................................................................................... 23

Table 4.2. Presence of apical vapor lock following positive pressure irrigation 1 mm short of the working length in roots instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08 ........................................................................................................................................................................................................................................... 24

Table 4.3. Vapor lock elimination using MDA in teeth instrumented with either V-taper or ProTaper Gold (Chi-square test)............................................................................................................................................................................................................................................................................................................ 27

Table 4.4. Vapor lock elimination using sonic agitation in teeth instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08 (Chi-square test) ........................................................................................................................................................................................................................................................................................................... 27

Table 4.5. Vapor lock elimination using ultrasonic agitation in teeth instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08 (Chi-square test) ........................................................................................................................................................................................................................................................................................................... 27

Table 4.6. Elimination of apical vapor lock using MDA in teeth instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08 ........................................................................................................................................................................................................................................................................................................... 28

Table 4.7. Elimination of apical vapor lock using sonic agitation with EndoActivator in teeth instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08 ........................................................................................................................................................................................................................................................................................................... 28

Table 4.8. Elimination of apical vapor lock using ultrasonic agitation with the ProUltra unit and a ISO size 15 U-file in teeth instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08 ........................................................................................................................................................................................................................................................................................................... 29

Table 4.9. Elimination of apical vapor lock using three methods: MDA with 50 strokes of a well fitting gutta percha cone seated to working length, sonic agitation using EndoActivator system 2 mm short of working length and ultrasonic agitation 2 mm short of working length. In the ultrasonic group, samples were first agitated at a low power setting using the ProUltra device, followed by medium and high power settings (Chi-square test) ........................................................................................................................................................................................................................................................................................................... 29
List of Figures

Figure 3.1. A photograph of an experimental model showing a sponge with two teeth positioned inside it and sealed with OpalDam (blue arrow). A slit made posteriorly to the teeth was for the PSP plate (green arrow) during radiographic exposure ................................................................. 20

Figure 3.2. A photograph of an experimental tooth converted into a closed system by the application of hot glue (blue arrow) around the apex................................. 21

Figure 3.3. A photograph showing the EndoActivator utilized for sonic agitation. The polymer tip chosen for use in the study was the yellow tip (15/0.02) (green arrow) ................................................................. 22

Figure 3.4. A photograph of the ProUltra unit utilized for ultrasonic agitation. The tip selected here was an ISO size U-file 15/0.02 (green arrow) ................................................................. 22

Figure 4.1. Presence of apical vapor lock (blue arrows) following positive pressure irrigation in tooth instrumented with V-taper 25/0.06 (A1) or ProTaper Gold F2 25/0.08 (A2) ......................... 25

Figure 4.2. Presence of AVL (blue arrow) in a root instrumented with V-taper 25/0.06 (A1). Elimination of AVL using MDA with 50 strokes of a well fitting GP cone (A2) .................. 30

Figure 4.3. Presence of AVL (blue arrow) in a root instrumented with ProTaper Gold F2 25/0.08 (A1). Elimination of AVL using MDA with 50 strokes of a well fitting GP cone (A2) ............... 30

Figure 4.4. Presence of AVL (blue arrow) in a root instrumented with V-taper 25/0.06 (A1). Elimination of AVL using MDA with 50 strokes of a well fitting GP cone (A2) ............... 31

Figure 4.5. Presence of AVL (blue arrow) in a root instrumented with ProTaper Gold F2 25/0.08 (A1). Elimination of AVL using MDA with 50 strokes of a well fitting GP cone (A2) ............... 31

Figure 4.6. Presence of AVL (blue arrow) in a root instrumented with V-Taper 25/0.06 (A1). AVL (blue arrow) still present following sonic agitation with EndoActivator (A2) ............... 32

Figure 4.7. Presence of AVL (blue arrow) in a root instrumented with ProTaper Gold F2 25/0.08 (A1). AVL (blue arrow) still present following sonic agitation with EndoActivator (A2) ............... 32

Figure 4.8. Presence of AVL (blue arrow) in a root instrumented with V-taper 25/0.06 (A1) .... 33

Figure 4.9. AVL (blue arrow) still present following ultrasonic agitation with an ISO size 15 U-file in a ProUltra unit at three different power settings: Low (A1), Medium (A2), High (A3) ... 33

Figure 4.10. Elimination of AVL using manual dynamic agitation with 50 strokes of a well fitting GP cone after ultrasonic agitation under different power settings shown above (A1-A3) failed to .......................................................................................................................... 34
**List of Abbreviations**

AVL: Apical vapor lock

BL: Buccolingual

CFD: Computational fluid dynamics

CsCl: Cesium chloride

EDTA- Ethylenediaminetetraacetic acid

GP: Gutta percha

ISO: International Organization for Standardization

MD: Mesiodistal

MDA: Manual dynamic agitation

NaOCl: Sodium hypochlorite

Ni-Ti: Nickel-Titanium

PPI: Positive pressure irrigation

PT: ProTaper

SEM: Scanning electron microscopy

US: Ultrasonic

VRF: Vertical root fracture

WL: Working length

WL-1: 1 mm short of working length

WL-3: 3 mm short of working length
Acknowledgements

I would like to thank the entire team at UBC Graduate Endo for making my journey through the program as smooth as possible. I thank my supervisor, Dr. Shen for her guidance along the entirety of the project and always making time to be there for her students when needed. I would also like to thank Dr. Haapasalo for sharing his great wealth of knowledge with us during his interactive lectures. Dr. Coil, thank you for accepting me into your program. I am extremely thankful for the opportunity given to specialize in a field which has been a passion of mine from the first endodontic lecture given to me in dental school. I also thank all of the clinical instructors at UBC Grad Endo. In particular, I thank Dr. Ektefaie for devoting his Friday afternoons to further our case management abilities and Dr. Hieawy for challenging me to become a better clinician. John, thank you for helping me with the statistics portion of my research. To all of my co-residents Tyler, Khalid, Sarah, Mike, Aleem, Hind, Meeta, Josh, Parisa, Eleni and Randy, thank you all for contributing to my growth as a clinician during these three years. Randy, I know you are somewhere up in Heaven looking down at us. You were one of the most amazing people to ever walk into my life. I miss the deep conversations we had. The friendship we shared will always be cherished.
Dedication

I dedicate this to my family and fiancé, Maria. Without your ongoing support, this would not have been possible. To my parents and brother, thank you for always being there for me, for your kindness and words of encouragement. Maria, thank you for the deep love and care you’ve shown me for the last 7 years. Your strong courage and great passion for anything you pursue in life have been inspiring. I cannot wait to see you blossom into an exceptional dentist.
Chapter 1: Introduction

1.1 Objective in Endodontics

Apical periodontitis is an inflammatory reaction of periradicular tissues in response to bacterial ingress of pulpal tissue [Nair et al., 2005]. As such, the main objective of root canal therapy is to prevent apical periodontitis or in the event it is already established, cure it by bacterial elimination [Ørstavik & Pitt Ford, 2008]. The classical study of Kakehashi et al. was the first of many to elucidate the infectious nature of apical periodontitis. Germ-free Fisher rats and conventional rats received surgical pulpal exposures. Only conventional rats developed pulpal necrosis and subsequent periapical abscess formation and not germ-free rats [Kakehashi et al., 1965]. Following this, Sundqvist [1976] revealed the variety of bacterial species involved by evaluating their composition in the endodontic infection, most of which were found to be strict anaerobes. The large diversity of bacterial species involved in the endodontic infection, coupled with the complexity of the root canal system, suggests it is highly unlikely that sterilization of this system can be achieved [Hess, 1925; Vertucci, 1984]. As a result, the aim of endodontic treatment is to disinfect the root canal system to a low enough threshold at which the body has the capacity to begin self-repair.

1.2 Mechanical instrumentation

Mechanical instrumentation is a crucial step to the start of endodontic treatment as it shapes the canal space in preparation for irrigation and aids in the initial reduction of bacterial load [Ingle & Zeldow, 1958; Grossman, 1981]. Although mechanical instrumentation alone lowers bacterial counts, it does not yield complete sterilization of the root canal system. Ingle and Zeldow
showed that 80% of infected root canals were still positive for bacterial cultures immediately following instrumentation. The number increased to 95.4% at the start of the second appointment [Ingle & Zeldow, 1958]. Byström and Sundqvist observed a bacterial load reduction of 100 to 1000-fold following stainless steel instrumentation of infected root canals. Despite these teeth undergoing five consecutive treatments, bacterial culturing was still positive in seven of the 15 teeth [Byström & Sundqvist, 1983]. Nickel-titanium (Ni-Ti) rotary files were introduced in the eighties to advance the instrumentation phase of treatment [Walia & Brantley, 1988]. Various studies have concluded that canals prepared with Ni-Ti files leave canals cleaner and cause fewer iatrogenic complications such as straightening, transportation and perforations when compared to stainless steel hand instruments [Esposito & Cunningham, 1995; Nagy et al., 1997]. These advantages over traditional stainless-steel hand instruments are credited to the greater flexibility and advanced file design features of Ni-Ti rotary files. Despite these advancements, Ni-Ti rotary files are also incapable of yielding a completely sterilized root canal system. Dalton et al. measured bacterial reduction in teeth instrumented with stainless steel hand files or Ni-Ti rotary files using physiologic saline as irrigant. All teeth with apical periodontitis, regardless of instrumentation type, showed positive bacterial cultures, whereas the vital counterparts were sterile [Dalton et al., 1998]. It is the complexity of the root canal anatomy that limits the effectiveness of mechanical instrumentation alone. Vertucci’s work in the 1980’s on more than 2000 cleared permanent molars elucidated this complexity by showing the existence of canal irregularities, presence of lateral canals, apical deltas, fins, webs and transverse anastomoses [Vertucci, 1984]. As a result, Ni-Ti rotary files are incapable of making contact with every wall of dentin. Micro-CT studies investigating cleaning effectiveness of Ni-Ti rotary files show that as much as 49% of walls remain untouched following instrumentation with the ProTaper system.
(Dentsply Sirona, York, PA) [Peters et al., 2003]. Even with the development of newer
generation of Ni-Ti files with designs set specifically to target the complex anatomy, no one file
on the market is capable of addressing the entirety of the root canal system. These shortcomings
of mechanical instrumentation alone highlight the importance of irrigating solutions as a
supplementary tool to disinfection. Therefore, chemical debridement via the use of an irrigant is
a necessary adjunct to mechanical instrumentation for killing microorganisms, flushing debris
and removing the smear layer from the canal system [Gulabivala et al., 2005].

1.3 Irrigant
Due to the limitations of mechanical instrumentation alone, using adjunct chemical disinfection
is necessary. The process of irrigation has a few objectives. First, an irrigant will act as a
lubricant for instruments during cleaning and shaping. Second, by means of flushing, it will
remove microorganisms, dentin chips and debris along with any additional tissue remaining
[Gulabivala et al., 2005].

1.3.1 Sodium hypochlorite (NaOCl)
First reports of sodium hypochlorite as an antimicrobial agent came from Koch and Pasteur in
the 19th century where they reported high bactericidal effectiveness [Sedgley, 2004]. It has a
broad spectrum antimicrobial activity and rapidly kills vegetative and spore forming bacteria,
fungi and viruses on contact [McDonnel et al., 1999]. The earliest report of sodium hypochlorite
use in endodontics was published in 1920 by Coolidge and Crane [Sedgley, 2004]. Currently, it
is the most commonly used irrigant in root canal therapy. Sodium hypochlorite is a strong base
with a pH > 11, and is one of the reasons for its antimicrobial effectiveness. Common
concentrations reported in the literature for clinical use include 0.5-6%. In water, sodium hypochlorite ionizes into sodium (Na+) and hypochlorite (OCl-) which then forms an equilibrium with hypochlorous acid. Hypochlorous acid contains chlorine, a strong oxidizing agent. Chlorine disrupts enzymatic activity and in doing so disrupts bacterial metabolic activity leading to bacterial death. Another mechanism of bacterial killing is achieved from the high pH of NaOCl due to the presence of hydroxyl ions. This causes phospholipid degradation, enzymatic inhibition and further metabolic disruption. There are three chemical reactions proposed to account for NaOCl’s ability to dissolve organic tissue. NaOCl, when in contact with organic tissue, acts as a solvent. Chlorine reacts with amino groups to form chloroamines (chloroamination reaction) and degrades fatty acids into soap and glycerol in what is known as the saponification reaction. The third reaction is a neutralization of the amino acids forming water and salt. NaOCl exerts its antimicrobial effects through the formation of hypochlorous acid, hydroxyl and chlorine ions while the breakdown of organic tissue is achieved through the saponification reaction of fatty acids [Estrela et al., 2002]. Tissue dissolution is crucial as any tissue left behind after chemomechanical preparation is a reservoir of nutrients for bacteria and potential for future endodontic failure [Peters, 2004].

1.3.2 Organic tissue dissolution

Grossman & Meiman [1982] reported sodium hypochlorite’s tissue dissolving ability by observing the dissolution of pulpal tissue in 20 minutes to 2 hours when a 5% NaOCl solution was used. Spano et al. studied the solvent effect of four concentrations of NaOCl solutions (0.1%, 1.0%, 2.5% and 5.0%) on bovine pulp tissue and residual chlorine pH levels following dissolution. The authors observed that all concentrations of NaOCl suffered a reduction in the
pH, however, the greater the initial concentration of sodium hypochlorite, the smaller the reduction of the pH and the greater the residual chlorine [Spanó et al., 2001]. This is important, as a high pH and free chlorine are responsible for NaOCl’s bactericidal activity. The effects of different concentration of NaOCl on tissue dissolution was also investigated by Hand and Smith. The authors found that dilutions of 5.25% NaOCl solution resulted in significant decrease in necrotic pulp tissue dissolution [Hand & Smith, 1978]. Naenni et al. studied the effects of various common irrigants (sodium hypochlorite, chlorhexidine, hydrogen peroxide and citric acid) on necrotic tissue obtained from the palates of pigs. The authors observed that only sodium hypochlorite showed tissue dissolving capabilities [Naenni et al., 2004]. The tissue dissolving abilities of NaOCl were further improved with the addition of mechanical agitation [Moorer & Wesselin, 1982].

1.3.3 Antimicrobial

The correlation between concentration and antimicrobial effectiveness shows conflicting results. Byström and Sundqvist [1985], and Cvek et al. [1976] independently observed lack of significant difference in antimicrobial effect between 0.5% and 5% NaOCl. In the study by Byström and Sundqvist, teeth with necrotic pulps and periapical radiolucency were included. Half of the teeth were irrigated with 0.5% NaOCl and the other half with 5% NaOCl following instrumentation. Bacterial quantity was measured at the end of the appointment. No significant difference was found between the two solutions [Byström & Sundqvist, 1985]. Contrary to this, several other studies have shown that diluted solutions of NaOCl are less effective at microbial reduction. In an in vitro study, Siqueira et al. studied the antimicrobial effect of three different concentrations (1%, 2.5% and 5.25%) of NaOCl in conjunction with instrumentation. Roots were inoculated
with *Enterococcus faecalis* prior to instrumentation and irrigation. Samples were transferred onto agar plates and colony forming units were measured. The authors observed that 5.25% NaOCl resulted in significantly higher killing of *E. faecalis* [Siquiera et al., 2000]. Wang et al. studied the effects of 2% and 6% NaOCl on 3-week-old *E. faecalis* biofilm using their novel dentin infection model. In this model, *E. faecalis* was inoculated into root dentinal tubules using centrifugation. Bacterial killing was measured using confocal scanning electron microscopy. The authors observed a 6% NaOCl solution had significantly higher bactericidal activity as compared to a 2% solution [Wang et al., 2012]. Estrela et al. observed excellent antimicrobial effects of 2% NaOCl on facultative bacteria (*Staphylococcus aureus, E. faecalis, Pseudomonas aeruginosa, Bacillus subtilis* and *Candida albicans*) using the agar diffusion test [Estrela et al., 2003]. In another study by Gomes et al., the authors observed that as the concentration of sodium hypochlorite increased, the time required to eliminate *E. faecalis* decreased. A concentration of 5.25% resulted in 100% growth inhibition with less than 30 seconds contact as compared to a 4.0% concentration which took 5 minutes to reach complete growth inhibition [Gomes et al., 2001].

### 1.4 Canal taper influence on irrigation

Effectiveness of chemomechanical preparation largely depends on the ability of the irrigant to penetrate the full length of the root canal system. This penetration is limited by the depth of the needle delivering the irrigant, a concern as Abou-Rass and Piccinino [1982] showed for irrigant delivery to be effective, needle placement must be in the apical third of the canal. Root canal size is one constraint on the ability of placing the needle into the apical third. Studies in the literature investigating root canal shaping have reported that a greater taper of the root canal results in
greater apical debridement during irrigation [Albrecht et al., 2004]. Boutsikoukis et al. used a computational fluid dynamic model to evaluate the fluid dynamics of irrigants within a root canal system that was instrumented using various tapers. In that study, the apical size was set at 0.30 mm and the root canal taper was set at either 2%, 4% or 6%. The authors observed that better irrigant flow was achieved in root canals with greater taper. This was the case irrespective of the depth of needle penetration [Boutsikoukis et al., 2010b]. Albrecht et al. [2004] and Huang et al. [2008] found similarly that greater tapers left less debris when compared to smaller tapers. However, needle depth was not standardized in these studies making it difficult to determine whether more debris was cleared as a result of a greater canal taper or that the needle was able to be inserted more apically. Contrary to the results of these studies, Abou-Rass and Piccinino [1982] demonstrated that an apical shaping to an ISO size 25 hand file with adequate coronal preflare is effective at flushing debris from the apical third of canals when compared to an apical preparation of ISO size 40. Although irrigant penetration is better achieved in canals with greater tapers, looking at antimicrobial effectiveness, Hockett et al. [2008] found no significant differences when comparing syringe irrigation in tapered canals instrumented with ProTaper F3 (30/0.09) and minimally tapered canals instrumented with 45/0.02.

1.5 Agitation of irrigants

Conventional irrigation utilizes syringe and needle under positive pressure to administer irrigant into the root canal system. Utilizing this method, irrigant penetration extends to only 1.0 mm beyond the needle tip, given that a clinically relevant flow rate between 0.01 ml/s - 0.260 ml/s is applied [Boutsikoukis et al., 2009]. Laminar flow created from syringe irrigation alone is insufficient at penetrating canal irregularities as a result of weak mechanical flushing [Gulabivala
et al., 2010]. As such, the penetration of irrigant and the success of chemomechanical preparation is limited by the depth of needle insertion. To overcome the shortcomings of conventional needle irrigation, various agitation techniques have been developed. Irrigant agitation enhances the physical effectiveness of the irrigant through the shear and streaming forces generated [Gulabivala et al., 2010]. This force creation can be created manually or by the use of mechanically driven instruments in the form of sonic and ultrasonic agitation.

1.5.1 Manual dynamic agitation

Manual dynamic agitation is a simple and cost-effective technique at replenishing and apically propagating irrigants [McGill et al., 2008]. It involves the movement of a well-fitting gutta percha cone in short vertical strokes seated to working length. The tight fit between the gutta percha and dentin wall will force irrigant apically. As a result of tissue pressure beyond the apical foramen, the irrigant will be displaced sideways and upwards. This replenishes irrigant while at the same time preventing irrigant extrusion beyond the apical foramen. McGill et al. compared manual dynamic agitation to RinsEndo, an automated pressure suction device, at the effectiveness of removal of a collagen bio-molecular film in roots. The authors found that manual dynamic agitation was significantly more effective at bio-molecular film removal and suggested that MDA is effective at hydro dynamically displacing and replacing sodium hypochlorite [McGill et al., 2008]. In the study, 100 strokes per 30 seconds was done equating to 3.3 Hz which has a higher frequency as compared to a frequency of 1.6 Hz generated by RinsEndo. A higher frequency used to agitate the irrigant is likely to cause greater turbulent flow. Caron et al. observed smear layer and debris removal after root canal instrumentation and irrigant agitation using MDA, EndoActivator (sonic) (Dentsply Sirona), RinsEndo and needle
irrigation only. The authors found that MDA and EndoActivator were equally effective at removing smear layer and significantly better than the other groups tested [Caron et al., 2010].

1.5.2 Sonic agitation

Tronstad et al. [1985] has been credited with introducing sonic instrumentation in endodontics. Sonically driven instruments utilize a frequency between 1-6 kHz. There is an oscillation amplitude difference between the node, near tip attachment and antinode, at tip of instrument, with maximum oscillation occurring at the latter [Walmsley, 1989]. This has been shown to be highly effective at facilitating penetration and renewal of an irrigant in the root canal system. The EndoActivator is a sonically driven device which can vibrate at a frequency of up to 10,000 cycles per minute. It utilizes the vibration of a flexible plastic tip in the root canal. The tip is available in three different sizes (Yellow 15/0.02, Red 25/0.04, Blue 35/0.04) and easily attaches to the sonically driven unit. Studies looking at the penetration of sonically agitated solutions show promising results. De Gregorio et al. studied the penetration of ethylenediaminetetraacetic acid (EDTA) into simulated lateral canals using sonic, ultrasonic and needle insertion. The sonic agitation was carried out using the EndoActivator for one minute at a depth of 2mm from the apex. The authors observed that EndoActivator and ultrasonic agitation led to similar penetration of EDTA into lateral canals and significantly better than needle insertion alone [de Gregorio et al., 2009]. Penetration of irrigant using sonic, ultrasonic and MDA was studied by Paragliola et al. under fluorescence microscopy. The group whose irrigant was agitated with ultrasonic device showed higher dentinal tubule penetration, followed by the EndoActivator [Paragliola et al., 2010]. Several other studies have evaluated the effectiveness of sonic agitation with regards to bacterial reduction. Investigating the effects of ultrasonic, EndoActivator, EndoVac and needle
insertion, Townsend and Maki [2009] found EndoActivator to be significantly better than EndoVac and needle insertion at reducing seven day old *E. faecalis* biofilm. In an in vitro study, Caron et al. evaluated root canal cleanliness following root canal instrumentation and irrigant agitation using MDA, EndoActivator, RinsEndo and needle irrigation only. Smear layer and debris removal was visualized under the scanning electron microscope (SEM). The authors showed that MDA and EndoActivator agitation of a 3% NaOCl/17% EDTA solution resulted in significantly cleaner canals compared to the other groups [Caron et al., 2010]. Shen et al. studied the bactericidal activity of ultrasonic and EndoActivator activated irrigants on a 21-day old biofilm grown on hydroxyapatite disks. Agitation was carried out for 1 or 3 min at a distance of 5mm from the disks. The EndoActivator showed highest bactericidal activity at both time points when observed under the confocal laser scanning microscope [Shen et al., 2010].

1.5.3 Ultrasonic agitation

Richman [1957] was the first to write about the application of ultrasonics to root canal therapy. Ultrasonic devices can be either magnetostrictive or piezoelectrically powered. As a result of magnetostrictive devices generating more heat, piezoelectrically driven ultrasonics are the preferred choice in endodontics [Plotino et al., 2007]. When endodontic files are used in an ultrasonic device with a handpiece, they oscillate longitudinally, in the frequency range of 24-42 kHz. These oscillations produce acoustic streaming, a vortex-like motion of the fluid that the file is in [Gulabivala et al., 2010]. The ultrasonic energy also creates gas-filled bubbles in this acoustic field, a phenomenon named cavitation [Ahmad et al., 1987]. These microscopic bubbles burst and in the process releasing heat. Ultrasonic agitation of irrigant has been shown to have a positive impact on chemical debridement. Bacterial reduction after ultrasonic irrigation was
evaluated clinically by Sjögren et al. Thirty-one teeth with necrotic roots and periapical radiolucencies were included in the study. Canals that were narrow, a headstrom file was used to instrument up to and ISO size 20 H-file. Larger canals were left untouched. All canals were irrigated with 0.5% NaOCl and ultrasonically agitated. Samples were tested for bacterial species using agar plates set for Enterococci, *Actinobacillus actinomycetemcomitans* and Brucella sp.

From the 31 roots investigated, nine were still positive for bacterial cultures at the end of the first appointment. Although most roots were bacteria free, a large number were still positive for bacterial species [Sjögren & Sundqvist, 1987]. One possible reason to explain this finding could be the concentration of NaOCl used. As comparison, Huque et al. looked at the effects of different concentrations of NaOCl on dentin debris and dental plaque removal using ultrasonics and visualized under SEM. The authors found ultrasonic agitation of higher concentrations of NaOCl 5.5% and 12% eradicated the bacteria, whereas lower concentrations of 0.5% and 2.5% did not [Huque et al., 1998]. Spoleti et al. inoculated extracted teeth with *S. aureus*, *E. coli* and *S. viridans* following canal instrumentation up to an ISO size 20 K-hand file. The authors observed that canals irrigated with saline and ultrasonically activated resulted in fewer number of surviving colonies as compared to saline irrigation alone [Spoleti et al., 2003].

### 1.6 Apical vapor lock

Vapor lock is the entrapment of air by the formation of gas bubbles during irrigant flow in a closed-ended channel [Pesce et al., 2010]. A tooth represents a closed system indeed, as any portal of exit from the root canal system such as an apical foramen or a lateral canal is enclosed by the periodontium. This also applies in a disease state where apical periodontitis has been diagnosed. In cases of apical periodontitis, the granulation tissue present exerts enough pressure
to prevent irrigant extrusion past the apical foramen. The entrapped air that has been formed is a physical phenomenon where bubble formation occurs when a fluid (irrigant) is progressed forward towards a closed end (apical foramen) [Gu et al., 2009]. A second way of bubble formation specifically pertaining to root canal treatment is by the reaction between sodium hypochlorite and organic tissue in the canal, creating ammonia and carbon dioxide [Gu et al., 2009]. To determine whether apical vapor lock (AVL) has an effect on irrigant penetration, Tay et al. compared debris removal in a closed and open system. To simulate a close-ended system, Tay et al. covered the root apices with hot glue and inserted into a clear PVS- filled Plexiglass tube. The open system was created by enlarging the apical foramen to an ISO size 30 K-file and attaching a straw to the apex. Teeth were instrumented to a size 50/0.04 and irrigated with 1.3% NaOCl using a 30-gauge close ended, side vented needle from 1 mm short of the working length. MTAD Biopure was delivered using the same needle and left for 5 minutes. Debris and smear layer removal were visualized using SEM and light microscopy. In a certain number of teeth, apical vapor lock was visualized radiographically by the use of cesium chloride (contrast solution), delivered with a 30-gauge close ended, side vented needle from 1 mm short of the working length. The authors observed significantly more debris present across the entirety of the root canal space in a close-ended system when compared to an open system. Furthermore, apical vapor lock was visualized in the apical third of teeth as a radiolucent space. This was only observed in a closed system and not in an open system. This was an important study as it set forth standards in studying the effects of apical vapor lock [Tay et al., 2010]. Boutsioukis et al. investigated various factors pertaining to the formation and elimination of apical vapor lock such as needle type, depth of needle insertion, flow rate and root canal size. Canal instrumentation was set at a size of 35/0.04 and 50/0.04 in artificial canals. Open ended and closed- ended
needles placed at either 3 mm short of working length or 1mm short and irrigated using 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 evaluated. The authors observed that increasing apical preparation size, higher flow rate, increasing needle penetration depth and using open ended needles decreased the size of the apical vapor lock. Interestingly, the authors showed that an established AVL can be eliminated if the needle is inserted to WL and delivering irrigant at a flow rate of 0.083ml/s or irrigant delivery at WL-1 or WL-3 using a rate of 0.26 ml/s [Boutsioukis et al., 2014].

1.7 Vertical root fractures

Vertical root fractures are bucco-lingually or mesio-distal fractures in the root. Clinically, it may cause an isolated vertical bony defect or sinus tract and it may also show radiographic bone pattern loss suggestive of vertical root fracture [Eleazer et al., 2012]. Vertical root fractures most commonly occur in endodontically treated teeth, with rare instances occurring in non-root filled teeth [Tamse, 1988]. Due to its poor prognosis, vertical root fractures are considered serious dental complications often resulting in tooth extraction. The incidence of vertical root fractures has been evaluated by a number of observational studies. In his clinical practice, Vire [1991] observed 116 endodontically treated teeth extracted over a period of one year. At the end of the follow up, 4.3% of the teeth studied were extracted due to vertical root fractures. In a similar study, Fuss et al. [1999] found that 11% of endodontically treated teeth were extracted as a result of vertical root fractures. The etiology of vertical root fractures is multifactorial. Studies show that excessive forces during instrumentation and obturation increase the incidence of VRF. Higher torque settings on rotary motors increase incidence of crack formation compared to lower
torque settings [Dane et al., 2016]. Another major factor that increases incidence of VRF is excessive tooth structure removal from either increased root canal enlargement during instrumentation or during post preparation [Wilcox et al., 1997]. Dentin thickness and overall remaining tooth structure have been shown to directly affect the strength of an endodontically treated tooth [Wilcox et al., 1997]. As stated previously, mechanical instrumentation is one major contributing factor to dentin loss alongside crack formation and propagation [Yoldas et al., 2012]. There are various Ni-Ti manufacturers on the market with varying tapers and apical sizes. These tapers can range from 0.04 mm to 0.12 mm. Krikeli et al. evaluated the effect of different instrument tapers on the fracture resistance of endodontically treated teeth. The authors measured the fracture resistance in teeth that were instrumented with ISO size 40 Mtwo rotary files with either an 0.04 or 0.06 taper. They observed that teeth instrumented with the 0.06 taper had a significant reduction in fracture resistance [Krikeli et al., 2018]. Zandbilgari et al. studied the force necessary to cause vertical fractures in roots instrumented with ISO size 40 FlexMaster 0.02 taper and ISO size 40 GT file 0.04 taper. The authors observed roots instrumented with the greater, 0.04 mm taper, were significantly weakened as compared to root preparation using the 0.02 mm taper [Zandbilgari et al., 2006]. Avoiding excessive dental removal is a balance between dentin conservation and adequate canal disinfection. Newer generation rotary instruments have been developed with that concept in mind. V-taper (SS White Dental, Lakewood, NJ) is a Ni-Ti rotary instrument with a maximal flute diameter of 0.69 mm for its 25/0.06 file, making it the smallest on the market today. Smaller maximal flute diameters allow clinicians to preserve pericervical dentin and in doing so increasing the fracture resistance to vertical root fractures.
Chapter 2: Rationale and Hypotheses

2.1 Rationale

Pericervical dentin is the dentin located 6 mm apical and 4 mm coronal to the crestal bone and plays a crucial role in the integrity of the tooth structure. Preservation of pericervical dentin can be achieved using conservative Ni-Ti instruments such as V-taper, with smaller maximal flute diameters. One concern with the use of conservative instrumentation, however, is the ability to effectively disinfect the apical third of roots. This study aims to investigate the effects of conservative instrumentation on the formation of apical vapor lock and its subsequent elimination, something yet to be done.

2.2 Hypotheses

1. There will be no difference in apical vapor lock formation during positive pressure syringe irrigation following Ni-Ti instrumentation using conventional, ProTaper Gold (Dentsply Sirona) and conservative, V-taper rotary systems (SS White Dental, Lakewood, NJ).

2. There will be no difference between sonic, ultrasonic and manual dynamic agitation in established apical vapor lock elimination.

2.3 Aims

1. To compare incidence of apical vapor lock formation during positive pressure syringe irrigation following conventional, ProTaper Gold and conservative, V-taper Ni-Ti instrumentation.

2. Comparative evaluation of established vapor lock elimination by sonic, ultrasonic and manual dynamic agitation.
Chapter 3: Materials and methods

This study was approved by the University of British Columbia Clinical Research Ethics Board (Certificate H15-02793)

Extracted maxillary lateral teeth were used in this study. Teeth were radiographed in the buccolingual and mesiodistal directions to ensure a single canal system was present. Teeth were also inspected for caries, resorption, calculus or soft tissue. Teeth with caries and resorption were excluded. Calculus and soft tissue was removed with a scaler. Working lengths were set at 20.0mm, 0.5mm short of the apical foramen. A dental operating microscope was used to confirm the working length by placing an ISO size 10 K file (Mani, Japan) and extending it until it was flush with the apical foramen. Teeth were coronally reduced if working length was longer than the 20.0mm set as standard. Teeth were randomly allocated to a group where they would be either instrumented with V-taper (25/0.06) or ProTaper Gold F2 (25/0.08). Teeth were further allocated to three agitation groups: MDA, sonic and ultrasonic agitation that would be utilized to eliminate apical vapor lock. Random allocation was achieved by randomly assigning teeth to the groups one day after radiographic exposure. To facilitate the experimentation and ensure that radiographs are taken at the exact same angle during every exposure, a synthetic sponge divided into two sections was used (Figure 3.1). In the first section, teeth within the same agitation group, one instrumented with V-taper and the other with ProTaper were secured within the sponge. OpalDam (Ultradent, South Jordan, UT) was used to secure the periphery of the teeth in order to prevent irrigant spilling onto the sponge during irrigation. The second section consisted of a slit made parallel to the teeth that would hold a PSP plate during radiographic exposure (Figure 3.1). Teeth were converted to a closed system prior to placement in the sponge. This was achieved by following the protocol set forth by Tay et al. [2010]. One slight modification made
was the placement of a well fitting gutta percha cone prior to sealing the apical foramen with hot glue (Figure 3.2). This was done with the intention of preventing hot glue from moving inside the root canal system while the hot glue was applied to the end of the roots. Except for the last 2.0 mm of root, each tooth was coated with nail varnish to ensure any lateral canals were sealed. Following nail varnish coating, hot glue was applied to the apical 4mm of root covering the apical foramen. Teeth were held vertically to minimize the possibility of hot glue entering the apical foramen. A well-fitting gutta percha with adequate tugback was selected from the respective matching system. Cones that were not fitting well were trimmed to ensure a positive tugback. Visualization of apical vapor lock required the use of a contrast agent that can be utilized in conjunction with sodium hypochlorite. Cesium chloride (CsCl; BioUltra, Sigma-Aldrich, St. Louis, MO) was the contrast agent of choice in this study. Based on previous work by Farmand, the optimal concentration of contrast agent was determined to be 40.0%, created by mixing 4.0 grams of CsCl into 10.0 ml of 6.0% NaOCl. At this concentration, adequate contrast was obtained to differentiate between dentin and presence of air bubbles in the system. It was also found that a 40.0% solution would not affect the physical properties of NaOCl. Contact angle between dentin and contrast solution was measured against dentin and pure 6.0% NaOCl. Farmand used radicular dentin (2.0 mm by 2.0 mm by 1.0 mm) from the coronal third of mandibular distal roots to compare differences between mixtures of differing concentrations of CsCl and pure 6.0% NaOCl. Although higher concentrations of CsCl at 45.0% and 50.0% created greater contrast, there was a significant decrease in contact angle as compared to pure 6.0% NaOCl [Farmand, 2019].
Part 1:
The first part of the study compared the frequency of apical vapor lock formation in 18 teeth instrumented with V-taper and 18 teeth instrumented with ProTaper Gold. Delivery of irrigant was achieved using 31-gauge closed-ended double side-port (NaviTip, Ultradent, South Jordan, UT) to within 1.0mm short of working length. In each tooth, 1.0 ml of contrast solution was delivered using a 5.0 ml syringe at a constant, non-automated flow rate of 4.0 ml/min (0.067 ml/s) using a stopwatch. BL radiograph was taken to visualize whether or not apical vapor lock was formed and incidence calculated. Prior to commencing to part two of the study, the contrast solution was replaced with saline using 31-gauge closed-ended double side-port (NaviTip, Ultradent, South Jordan, UT) and paper point dried. BL radiographs were taken to ensure the complete removal of contrast agent from the root canal.

Part 2:
The second part of the study examined the effectiveness of apical vapor lock elimination once established. Irrigant was delivered using 31-gauge closed-ended double side-port (NaviTip, Ultradent, South Jordan, UT) to within 1.0 mm short of working length. In each tooth, 1.0 ml of contrast solution was delivered using a 5.0 ml syringe in 20 seconds at a constant flow rate of 4.0 ml/min (0.067 ml/s). BL radiographs were taken to ensure presence of apical vapor lock prior to agitating the solutions. The following agitation steps were performed only on samples with apical vapor lock. Once apical vapor lock was established, the sample of 36 teeth underwent irrigant agitation using the techniques they were randomly allocated to prior to the start of the study. Each agitation group consisted of 12 teeth, six of which were instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08.
Manual Dynamic Agitation – 50 strokes

Manual dynamic agitation was performed using a well fitted gutta percha cone seated to working length with 50 strokes completed at an amplitude of 2-3 mm for 35 seconds (frequency of 86 strokes/min), measured using a stopwatch. BL radiographs were taken to assess presence/absence of apical vapor lock. The gutta percha cones used for teeth instrumented with ProTaper Gold F2 was the corresponding ProTaper F2 cone. Teeth instrumented with V-taper used the corresponding 25/0.06 taper cone from SS white.

Sonic Agitation - EndoActivator

EndoActivator was used to achieve sonic agitation (Figure 3.3). As per manufacturers recommendation, the EndoActivator tip (Yellow- 15/0.02) was placed 2.0 mm short of the working length. The solution was agitated for 30 seconds with short vertical amplitudes. BL radiographs were taken to assess elimination of apical vapor lock.

Ultrasonic Agitation

An ISO size 15 U-file (NSK, Nakanishi, Tochigi, Japan) was secured onto the The ProUltra piezo ultrasonic unit and handpiece (Figure 3.4). The U-file was placed 2.0 mm short of working length and kept stable in that position while agitating the solution for 30 seconds. BL radiographs were taken to assess presence of apical vapor lock. The power setting of the ultrasonic unit was set at four (low power). In teeth that AVL was still present, agitation was further carried for another 30 seconds at a medium power setting of eight. BL radiographs were taken at this time and assessed for AVL. Once again, in teeth where AVL was still present, the power setting was
increased to a high-power setting of 12 and teeth were again agitated for 30 seconds. BL radiographs were taken to assess for AVL.

**Figure 3.1.** A photograph of an experimental model showing a sponge with two teeth positioned inside it and sealed with OpalDam (*blue arrow*). A slit made posteriorly to the teeth was for the PSP plate (*green arrow*) during radiographic exposure.
Figure 3.2. A photograph of an experimental tooth converted into a closed system by the application of hot glue (blue arrow) around the apex.
Figure 3.3. A photograph showing the EndoActivator utilized for sonic agitation. The polymer tip chosen for use in the study was the yellow tip (15/0.02) (green arrow).

Figure 3.4. A photograph of the ProUltra unit utilized for ultrasonic agitation. The tip selected here was an ISO size 15/0.02 U-file (green arrow).
Chapter 4: Results

Following positive pressure irrigation using syringe and needle 1 mm short of working length, the results indicate that apical vapor lock was present in 13/18 (72.2%) teeth instrumented with V-taper 25/0.06 and present in 14/18 (77.8%) teeth instrumented with ProTaper Gold F2 25/0.08 (Table 4.2). Figure 4.1 illustrates an example of apical vapor lock formation following PPI in a tooth instrumented with V-taper (A1) and ProTaper Gold (A2). Using the Chi-Square test, there was no statistically significant difference ($p>0.05$) in the formation of apical vapor lock following positive pressure irrigation in teeth instrumented either with V-taper or ProTaper Gold (Table 4.1).

<table>
<thead>
<tr>
<th>Rotary instrument</th>
<th>Vapor Lock Presence</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YES</td>
<td>NO</td>
<td>Significance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N (%)</td>
<td>N (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V-taper</td>
<td>13 (72.2%)</td>
<td>5 (27.8%)</td>
<td>$P &gt; 0.05$</td>
<td></td>
</tr>
<tr>
<td>Pro-taper</td>
<td>14 (77.8%)</td>
<td>4 (22.2%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1. Presence of apical vapor lock following positive pressure irrigation 1 mm short of the working length in roots instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08 (Chi-square test).
<table>
<thead>
<tr>
<th>Tooth #</th>
<th>Rotary System</th>
<th>Presence of apical vapor lock</th>
</tr>
</thead>
<tbody>
<tr>
<td>V.MDA.1</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.MDA.2</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.MDA.3</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.MDA.4</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.MDA.5</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.MDA.6</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.S.1</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.S.2</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.S.3</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.S.4</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.S.5</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.S.6</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.US.1</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.US.2</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.US.3</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.US.4</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.US.5</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.US.6</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.MDA.1</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.MDA.2</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.MDA.3</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.MDA.4</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.MDA.5</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.MDA.6</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.S.1</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.S.2</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.S.3</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.S.4</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.S.5</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.S.6</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.US.1</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.US.2</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.US.3</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.US.4</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.US.5</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.US.6</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
</tbody>
</table>

**Table 4.2.** Presence of apical vapor lock following positive pressure irrigation 1 mm short of the working length in roots instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08.
Figure 4.1. Presence of apical vapor lock (*blue arrows*) following positive pressure irrigation in tooth instrumented with V-taper 25/0.06 (A1) or ProTaper Gold F2 25/0.08 (A2).
Once apical vapor lock presence was confirmed radiographically, the three different agitation modalities were investigated at the effectiveness of apical vapor lock elimination. Manual dynamic agitation with 50 strokes of a well fitting gutta percha cone seated to working length eliminated apical vapor lock in 5/6 teeth instrumented with V-taper 25/0.06 and in 6/6 teeth instrumented with ProTaper Gold F2 25/0.08 (Table 4.6). There was no statistically significant difference \( (p>0.05) \) in the elimination of apical vapor lock by manual dynamic agitation in teeth either instrumented with V-taper 25/0.06 or ProTaper Gold F2 25/0.08 as per the Chi-square test (Table 4.3). An example of the elimination of apical vapor lock in teeth instrumented with V-taper 25/0.06 using MDA is illustrated in Figures 4.2 & 4.4, while Figures 4.3 & 4.5 illustrates the elimination of AVL also using MDA in teeth instrumented with ProTaper F2 25/0.08.

Furthermore, results indicate no statistically significant difference \( (p>0.05) \) in the elimination of apical vapor lock by sonic agitation with EndoActivator and ultrasonic agitation with an ISO size 15 U-file in a ProUltra unit in teeth either instrumented with V-taper 25/0.06 or ProTaper Gold F2 25/0.08 (Table 4.4 & 4.5). Figures 4.6 & 4.7 illustrate the inability of sonic agitation with EndoActivator to eliminate AVL in teeth instrumented with V-taper and ProTaper Gold, respectively. Figure 4.8 illustrates the presence of AVL in a root instrumented with V-taper.

Figure 4.9 shows the inability of ultrasonic agitation at three different power settings; low (A1), medium (A2) and high (A3) at eliminating apical vapor lock established as seen in Figure 4.8. Figure 4.10 illustrates the elimination of AVL using MDA in the exact same sample where ultrasonic agitation failed to. Comparing the effectiveness of the three different agitation modalities, regardless of what rotary system was used to instrument the roots, manual dynamic agitation with 50 strokes of a well fitting gutta percha cone seated to working length was significantly more effective \( (p<0.001) \) at eliminating apical vapor lock when compared to sonic
agitation with EndoActivator and ultrasonic agitation with an ISO size 15 U-file in a ProUltra unit (Table 4.9).

<table>
<thead>
<tr>
<th>Rotary instrument</th>
<th>Vapor Lock Elimination using MDA</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YES</td>
<td>NO</td>
<td>Significance</td>
</tr>
<tr>
<td>V-taper</td>
<td>5 (72.2%)</td>
<td>1 (27.8%)</td>
<td>P &gt; 0.05</td>
</tr>
<tr>
<td>Pro-taper</td>
<td>6 (100%)</td>
<td>0 (0%)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3. Vapor lock elimination using MDA in teeth instrumented with either V-taper or ProTaper Gold (Chi-square test).

<table>
<thead>
<tr>
<th>Rotary instrument</th>
<th>Vapor Lock Elimination using Sonic agitation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YES</td>
<td>NO</td>
<td>Significance</td>
</tr>
<tr>
<td>V-taper</td>
<td>0 (0.0%)</td>
<td>6 (0.0%)</td>
<td>P &gt; 0.05</td>
</tr>
<tr>
<td>Pro-taper</td>
<td>0 (0.0%)</td>
<td>6 (0.0%)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4. Vapor lock elimination using sonic agitation in teeth instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08 (Chi-square test).

<table>
<thead>
<tr>
<th>Rotary instrument</th>
<th>Vapor Lock Elimination Using Ultrasonic agitation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YES</td>
<td>NO</td>
<td>Significance</td>
</tr>
<tr>
<td>V-taper</td>
<td>0 (0.0%)</td>
<td>6 (0.0%)</td>
<td>P &gt; 0.05</td>
</tr>
<tr>
<td>Pro-taper</td>
<td>0 (0.0%)</td>
<td>6 (0.0%)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5. Vapor lock elimination using ultrasonic agitation in teeth instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08 (Chi-square test).
<table>
<thead>
<tr>
<th>Tooth #</th>
<th>Rotary System</th>
<th>Elimination of AVL</th>
</tr>
</thead>
<tbody>
<tr>
<td>V.MDA.1</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.MDA.2</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.MDA.3</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.MDA.4</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.MDA.5</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>V.MDA.6</td>
<td>V-taper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.MDA.1</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.MDA.2</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.MDA.3</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.MDA.4</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.MDA.5</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
<tr>
<td>PT.MDA.6</td>
<td>ProTaper</td>
<td>YES</td>
</tr>
</tbody>
</table>

Table 4.6. Elimination of apical vapor lock using MDA in teeth instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08.

<table>
<thead>
<tr>
<th>Tooth #</th>
<th>Rotary System</th>
<th>Elimination of AVL</th>
</tr>
</thead>
<tbody>
<tr>
<td>V.S.1</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.S.2</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.S.3</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.S.4</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.S.5</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.S.6</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.S.1</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.S.2</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.S.3</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.S.4</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.S.5</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.S.6</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
</tbody>
</table>

Table 4.7. Elimination of apical vapor lock using sonic agitation with EndoActivator in teeth instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08.
### Table 4.8. Elimination of apical vapor lock using ultrasonic agitation with the ProUltra unit and a ISO size 15 U-file in teeth instrumented with either V-taper 25/0.06 or ProTaper Gold F2 25/0.08.

<table>
<thead>
<tr>
<th>Tooth #</th>
<th>Rotary System</th>
<th>Elimination of AVL</th>
</tr>
</thead>
<tbody>
<tr>
<td>V.US.1</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.US.2</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.US.3</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.US.4</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.US.5</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>V.US.6</td>
<td>V-taper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.US.1</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.US.2</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.US.3</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.US.4</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.US.5</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
<tr>
<td>PT.US.6</td>
<td>ProTaper</td>
<td>NO</td>
</tr>
</tbody>
</table>

### Table 4.9. Elimination of apical vapor lock using three methods: MDA with 50 strokes of a well fitting gutta percha cone seated to working length, sonic agitation using EndoActivator system 2 mm short of working length and ultrasonic agitation 2 mm short of working length. In the ultrasonic group, samples were first agitated at a low power setting using the ProUltra device, followed by medium and high power settings (Chi-square test).

<table>
<thead>
<tr>
<th>Agitation method</th>
<th>Vapor Lock Elimination</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td></td>
<td>N (%)</td>
<td>N (%)</td>
</tr>
<tr>
<td>MDA</td>
<td>11/12</td>
<td>1/12</td>
</tr>
<tr>
<td>Sonic</td>
<td>0/12</td>
<td>12/12</td>
</tr>
<tr>
<td>Ultrasonic (Low)</td>
<td>0/12</td>
<td>12/12</td>
</tr>
<tr>
<td>Ultrasonic (Medium)</td>
<td>0/12</td>
<td>12/12</td>
</tr>
<tr>
<td>Ultrasonic (High)</td>
<td>0/12</td>
<td>12/12</td>
</tr>
</tbody>
</table>
Figure 4.2. Presence of AVL (blue arrow) in a root instrumented with V-taper 25/0.06 (A1). Elimination of AVL using MDA with 50 strokes of a well fitting GP cone (A2).

Figure 4.3. Presence of AVL (blue arrow) in a root instrumented with ProTaper Gold F2 25/0.08 (A1). Elimination of AVL using MDA with 50 strokes of a well fitting GP cone (A2).
Figure 4.4. Presence of AVL (blue arrow) in a root instrumented with V-taper 25/0.06 (A1). Elimination of AVL using MDA with 50 strokes of a well fitting GP cone (A2).

Figure 4.5. Presence of AVL (blue arrow) in a root instrumented with ProTaper Gold F2 25/0.08 (A1). Elimination of AVL using MDA with 50 strokes of a well fitting GP cone (A2).
Figure 4.6. Presence of AVL (blue arrow) in a root instrumented with V-Taper 25/0.06 (A1). AVL (blue arrow) still present following sonic agitation with EndoActivator (A2).

Figure 4.7. Presence of AVL (blue arrow) in a root instrumented with ProTaper Gold F2 25/0.08 (A1). AVL (blue arrow) still present following sonic agitation with EndoActivator (A2).
Figure 4.8. Presence of AVL (*blue arrow*) in a root instrumented with V-taper 25/0.06 (A1).

Figure 4.9. AVL (*blue arrow*) still present following ultrasonic agitation with an ISO size 15 U-file in a ProUltra unit at three different power settings: Low (A1), Medium (A2), High (A3).
Figure 4.10. Elimination of AVL using manual dynamic agitation with 50 strokes of a well fitting GP cone after ultrasonic agitation under different power settings shown above (A1-A3) failed to.
Chapter 5: Discussion

The current study evaluated the dynamics of apical vapor lock formation in a closed system. This was necessary in order to simulate in vivo conditions whereby the bony socket of a tooth encloses the apical foramen preventing fluid and gas exchange with the external environment. Work done previously by Tay et al. illustrated the importance of studying apical vapor lock in a closed system, as an open system often overestimates the efficacy of apical irrigation. The authors observed significantly more debris and smear layer when irrigation was conducted in a closed system. The authors largely contributed this due to apical vapor lock formation, present only in a closed system [Tay et al., 2010]. One way to evaluate apical vapor lock is indirectly, by measuring the effect of apical irrigation on smear and debris removal. A limitation in these studies however, is that only a certain portion of the specimen is often examined and may not be an accurate representation for the rest of the system. This becomes important in observing AVL where its occurrence is in a particular portion of the root canal (0.0-2.0 mm from apical foramen). If the specimen studied does not correlate with the location of AVL, correlation of results would be inappropriate. Instead, in the current study, AVL was evaluated radiographically using a contrast agent during 6.0% NaOCl irrigation. One concern, however, with the use of a contrast agent is its potential influence on the physical properties of NaOCl. Dentin wettability has a direct effect on surface tension of the solution to dentin and can therefore effect the likelihood of AVL formation. Decreasing the surface tension of an irrigant will increase the wetting ability of dentin which may lead to better irrigant penetration. Farmand evaluated the wetting ability of different concentrations of CsCl on NaOCl by measuring the contact angle between the solutions and dentin. The contact angle of a pure 6.0% NaOCl solution
was compared to a 40% contrast solution (4.0 grams CsCl in 10ml of 6.0% NaOCl). The results showed no significant differences between the two contact angles.

In order to simulate clinical conditions as closely as possible, teeth included in the study were freshly extracted and instrumented as soon as possible to minimize tissue breakdown. Furthermore, crowns were preserved to provide a slight reservoir for the irrigant, unlike most other studies where crowns are resected for easier experimentation. Following instrumentation, debris was not flushed out with irrigant prior to contrast irrigation. This was done purposefully to ensure tissue presence. Tissue presence is important as part of the apical vapor lock hypothesis is that NaOCl reacts with tissue to produce ammonia and carbon dioxide [Gu et al., 2009]. As this was an ex vivo study, limitations do exist. Teeth have variable morphologies and root curvatures which is impossible to control and therefore difficult to standardize. These limitations also translate to when comparing results to other studies. There are many variables that have the potential to affect apical vapor lock. Such variables include taper of instrument to shape canals, needle type and size, depth of insertion and flow rate, amongst the previously mentioned variability in the morphology and root curvatures of teeth [Boutsioukis et al., 2010a].

Current movement in endodontics is the preservation of pericervical dentin, the part of dentin extending 6 mm apical and 4 mm coronal to the crestal bone. Pericervical dentin is responsible for the distribution of occlusal stresses along the long axis of the root making its preservation crucial [Clark et al., 2013]. Unnecessary loss of pericervical dentin weakens the root and thus, predisposing it to vertical root fractures [Clark et al., 2013]. One way to conserve pericervical dentin is by using conservative instrumentation. As a result, V-taper was included in this study due to its conservative maximal flute diameter set at 0.69 mm for the 25/0.06 file. ProTaper Gold
F2 25/0.08, also a variable taper file, was selected for comparison as it is the most widely used endodontic rotary file making it relevant to most clinicians. Irrigant was delivered using a syringe and 31-gauge close-ended, side-vented needle. A 31-gauge needle was chosen in order to be able to deliver irrigant to within 1mm short of the WL in canals instrumented with V-taper. Comparing 30-gauge and 31-gauge close-ended, side-vented needle, Boutsioukis et al. [2010a] observed similar patterns of flow. The current study utilized a flow rate of 4.0ml/min (0.067 ml/s). This was chosen as any flow rate greater than 4.0ml/min failed to show significant improvement in irrigant penetration beyond the needle tip [Park et al., 2013]. This flow rate was not automated due to inconsistent flow rates established with an automated irrigation pump using a 31-gauge needle during pilot studies [Boutsioukis et al., 2007; Farmand, 2019]. The flow rate was therefore influenced by the strength of operator, length of finger, barrel volume and needle size [Boutioukis et al., 2010b]. A 5.0 ml syringe was used in this study because the smaller plunger requires less effort to deliver the irrigant. Manual dynamic agitation with 100 strokes of gutta percha was analyzed in numerous previous studies. This, however, may seem laborious by clinicians and discourage them from use. Farmand evaluated AVL elimination using various numbers of strokes and found 50 strokes administered over 35 seconds to be significantly effective at eliminating AVL and therefore 50 was the number of strokes chosen for the current study. Importantly, at this frequency, contrast mixture was confined to the root canal system as radiographic visualization did not show extrusion past the apical foramen. This was a similar finding to the work of Parente et al. and Farmand but in contrast with Boutsioukis et al. [Parente et al., 2010; Boutsioukis et al., 2014; Farmand, 2019]. Using water to simulate a closed system, Boutsioukis et al. observed significant extrusion when performing MDA at a frequency of 90
strokes/min. Water does not confer the same amount of pressure resistance as glue and maybe one reason for this difference.

In the current study, the incidence of apical vapor lock formation following positive pressure syringe needle irrigation in roots instrumented with conventional or conservative instrumentation was evaluated. AVL was found in 75.0% of total samples, 72.2% and 77.8% of samples instrumented with V-taper and ProTaper Gold, respectively. These results are similar to another ex-vivo study where 70.0% of the samples irrigated showed AVL. Canals were instrumented to a size 30/0.06 taper and irrigated using a contrast mixture at an unknown flow rate through a 30-gauge close-ended side vented needle, 2mm short of WL [Sáinz-Pardo et al., 2014]. In another study, Boutsioukis et al. utilized computational fluid dynamics (CFD) along with an in-vitro study to evaluate effect of flow rate and canal size on AVL after irrigation with 30-gauge close ended needle. The authors observed that AVL formed in all cases irrespective of canal shaping (35/0.04 or 50/0.04) and needle insertion (1 mm or 3 mm short of WL) so long as a low flow rate of 2.0ml/min was utilized [Boutsioukis et al., 2014]. Similarly to the current study, canal shaping (25/0.06 or 25/0.08) did not yield significant differences in apical vapor lock formation. Another similar study to the present one showed AVL formation in 100% of cases after instrumentation to a size F4 (40/0.06 mm) using ProTaper. EndoActivator eliminated AVL in 90% of cases. US eliminated AVL in 80% of cases and MDA in only 50% [Agarwal et al., 2017]. Depth of needle insertion, needle size and flow rate all play significant contributions to the formation of AVL during PPI which may account for the discrepancy in results between the current study [Boutsioukis et al., 2010b]. There were also differences in results with regards to the effectiveness of AVL elimination. In the current study, MDA eliminated AVL in 92% of cases as
compared to 50% in the study mentioned above. In the current study, MDA was performed using a system matching, well-fitting gutta percha cone with adequate tug back using 50 strokes. On the other hand, the team of Agarwal performed MDA using an ISO size 15 K-file. A tight fit between gutta percha cone and dentin wall will force the irrigant apically and given that there is tissue pressure beyond the apical foramen, the irrigant will be displaced sideways and upwards, a more effective approach compared to a hand file [Gu et al., 2009]. Agarwal utilized the EndoActivator for sonic agitation, however, the EndoActivator in their study was set at 6,000 Hz, significantly lower than the power setting of 10,000 Hz in the present study. In anterior teeth where a pulp chamber to act as a reservoir is limited, a higher frequency is more likely to displace the irrigant outwards, escaping through the access cavity. This was precisely the results observed in the current study. Significantly less irrigant, as based on amount of contrast agent visualized radiographically, remained in the root canal system following EndoActivator agitation and hence, lack of AVL elimination. Ultrasonic agitation eliminated 80% of AVL, less so than an EndoActivator. Limitation of the ultrasonic system stems from its function whereby multiple nodes and anti-nodes exist around the extent of the file whereas sonic agitation works at only one single negative and positive node. The greatest oscillation occurs at the anti-nodes, while minimal at the nodes [Walmsley et al., 1987]. Clinically, this translates to a poorer performance if the oscillating file makes contact with the dentin wall. Ahmad et al. [1987] observed the formation of acoustic streaming only in instances where a file was freely oscillating in a solution. Similarly, cavitation does not occur at times when a file makes contact with the dentin wall [Lumley et al., 1988]. Contact with the dentin wall also increases the potential for iatrogenic damage such as transportations, ledges and perforations, particularly in curved canals [Caron et al., 2010]. On the other hand, the movement generated in sonic agitation does not undergo
changes by contacts with the dentinal walls and iatrogenic damage is less likely to occur as the polymer used for oscillation is highly flexible.

The high effectiveness of MDA in the elimination of apical vapor lock may be due to several contributing factors. The close adaptation of a well-fitting GP cone with the dentinal wall generates adequate intracanal pressure to cause the displacement of irrigant to more areas. The pumping motion of GP also creates a viscously dominated flow as compared to the laminar flow observed with PPI. This viscous flow may allow for better displacement and renewal of the irrigant [Gu et al., 2009].

Potential future studies can investigate the difference in apical vapor lock formation between different conservative Ni-Ti rotary files that differ in their taper (constant versus variable). Such example is the Vortex Blue 0.04 mm constant taper and the variable taper rotary system, V-taper. Studies investigating apical vapor lock formation using a variable taper file such as ProTaper generally find higher incidences of apical vapor lock formation as compared to files with constant taper, such as Vortex Blue. Teeth shaped with fixed 0.06 or 0.04 tapers have found AVL formation in 70% [Sáinz-Padro et al., 2014] and 62.5% [Boutsioukis et al., 2014] of cases. On the other hand, teeth instrumented with a variable taper, such as ProTaper, show AVL presence in 100% of cases [Agarwal et al., 2017]. One factor that may contribute to these findings is that a constant taper design provides equal and continuous coronal space for irrigant that is flowing back in a turbulent manner. This coronal movement of turbulent flow allows for better irrigant penetration apically and a greater effect on AVL elimination [Bronnec et al., 2010].
Chapter 6: Conclusion

Incidence of apical vapor lock visualized radiographically using a contrast agent formed at equal frequency in roots instrumented with V-taper (25/0.06) and ProTaper Gold F2 (25/0.08). Manual dynamic agitation with 50 strokes of a well-fitting gutta percha cone is effective at eliminating apical vapor lock, regardless of rotary system used to instrument roots. Sonic agitation with EndoActivator and ultrasonic agitation with an ISO size 15 U-file were unsuccessful at eliminating apical vapor lock.

Overall findings of this study:

1. Incidence of apical vapor lock is high following instrumentation and positive pressure irrigation.
2. Canal instrumentation, regardless of whether a conservative or conventional rotary system was used, did not have an impact on incidence of apical vapor lock formation.
3. Manual dynamic agitation with 50 strokes of a well-fitting gutta percha cone was effective at eliminating apical vapor lock in roots instrumented with conservative and conventional rotary files.
Works Cited


