

**EVALUATION OF ULTRASONIC IRRIGATION SYSTEMS FOR
DEBRIS AND SMEAR REMOVAL IN ROOT CANALS: A SCANNING
ELECTRON MICROSCOPE STUDY**

by

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Abstract

Objective: The aim of this study was to compare the efficacy of continuous flow ultrasonic irrigation systems to conventional syringe irrigation in removing debris and smear layer in straight and curved root canals.

Methods: Twenty-four maxillary recently extracted anterior teeth of curvature less than 10 degrees and 24 mesial roots of mandibular molars with a curvature between 15-30 degrees were instrumented to size 40, 0.04 taper and 35, 0.04 taper, respectively, using 3% sodium hypochlorite. The teeth were divided into three experimental groups according to the final irrigation technique: conventional syringe irrigation with a 30 gauge side vented needle, the PiezoFlow Ultrasonic irrigation system, and the VPro StreamClean Ultrasonic irrigation system. In all experimental groups, 15 mL of 3% sodium hypochlorite was used after instrumentation. Both ultrasonic systems were set at a flow rate of 15 mL/min and used for 1 minute at the ultrasonic power setting recommended by the manufacturer. This was followed by 3 mL of 17% EDTA for 2 minutes and 2 mL of sterile water. The teeth were sectioned and prepared for scanning electron microscope observation to assess the presence of debris and smear layer at the apical level (1, 3, 5 mm) with 200x and 1000x magnification, respectively. The debris was graded using Adobe Photoshop CS5 and two calibrated observers using a five-score scale graded the smear. All grading was blinded. The debris data was analyzed using one-way analysis of variance with Dunnett's test and the smear layer scores were analyzed using Kruskal Wallis.

Results: Concerning debris removal, no significant differences among groups were detected, however, the PiezoFlow Ultrasonic system approached significance at the 1 and 3 mm levels

in the straight canals. The PiezoFlow Ultrasonic system resulted in significantly more smear layer removal at the 1 mm level in the straight canals compared to conventional syringe irrigation.

Conclusion. The final irrigation techniques were unable to completely remove debris or smear layer from the apical 5 mm of the straight and curved canals, however, the PiezoFlow removed significantly more smear layer at the 1 mm level in straight canals.

Preface

The research question of this project was identified and designed by Mark Parhar under the guidance of Dr. Markus Haapasalo and Dr. Ya Shen. All the sample preparation and image acquisition was done by Mark Parhar. The collected data was analyzed by Mark Parhar and Dr. Ya Shen. Mark Parhar prepared the Manuscript with editing by Dr. Ya Shen and Dr. Markus Haapasalo.

The study was approved by the University of British Columbia Office of Research Services, Clinical Research Ethics Board (Certificate Number: H11-03354)

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List of Abbreviations

EDTA: ethylenediaminetetraacetic acid

NaOCl: sodium hypochlorite

NiTi: nickel-titanium

PUI: passive ultrasonic irrigation

SEM: scanning electron microscopy

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Research has been something I have enjoyed in the past but it wasn't until I started my Master's project that I realized what proper research is and how to do it in an effective manner. I gained thorough insight into endodontics by doing this research project and it has certainly enhanced my clinical education. I want to thank Dr. Haapasalo for supervising my project and giving me such great insight into the research world of endodontics. I have learned a great deal with your tutelage. Also, I want to thank Dr. Ya Shen in her co-supervisor role with my project. The feedback you have given me has always been very helpful and always delivered with a smile and encouragement. Also, I want to thank Dr. Jeff Coil for his participation on my committee, as well as his fantastic guidance as my program director (and fishing guide!) and Dr. Don Brunette for his amazing insight into statistics and always having an open door for any questions that I had.

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Dedication

There is only one person that I can really dedicate this to and that is my incredible wife Victoria. There have been many others who have guided me along the journey of my life and career and I am forever grateful for all of those who have touched me in one way or another. However, I would not be the person who I am today nor would I be at this place today without the support, caring, friendship, compassion, kindness, enthusiasm, and deep love that you have given me.

I dedicate this to you as a symbol of my deep gratitude and love and I look forward to spending the rest of my life making every moment with you and our children as happy and special as possible, as that is what you deserve.

Chapter 1: Introduction

The role of microorganisms and their by-products in the pathogenesis of pulp necrosis and apical periodontitis has been well established (Kakehashi et al, 1965; Bergenholtz, 1974; Sundqvist, 1976; Möller et al 1981). Apical periodontitis is an inflammatory process that presents as a host defense response to the microbial challenge of the infected root canal system (Nair, 2004). This encounter results in rapid destruction of the periradicular tissues; therefore, the goal of endodontic therapy is the prevention and treatment of apical periodontitis (Ørstavik & Pitt Ford, 2008). Controlling the pulpal and periradicular infections can create an environment conducive to healing. Traditionally, this is achieved with the use of instruments, irrigants, and intracanal medicaments to mechanically and chemically debride the root canal system (Haapasalo et al, 2005). Hand and rotary instrumentation techniques shape the root canal, remove infected dentin, and facilitate the delivery of irrigants throughout the root canal system (Siqueira et al, 1999). The instrumentation must be complemented with irrigation that will flush out pulp tissue, dentin debris and microbes, in addition to decreasing the microbial load chemically (Haapasalo et al, 2010). Therefore, chemomechanical preparation is considered to be one of the most important factors for root canal disinfection. However, with the use of existing endodontic instruments, techniques and materials it is impossible to shape and clean the root canal system completely, even when the highest standards are followed (Siqueira et al, 1997; Siqueira et al, 2002). Consequently, endodontic failure can still occur as there are regions in the root canal system that cannot properly be disinfected (Nair et al, 2005).

The root canal morphology is a complex system consisting of a lateral canals, isthmuses, fins, anastomoses, apical deltas and accessory canals, in addition to the main canal (Hess & Zürcher, 1925). This complex nature makes complete debridement and disinfection extremely challenging as the instruments and irrigants fail to penetrate into the confined areas, allowing bacteria to survive. There is substantial evidence that apical periodontitis is a biofilm-induced disease (Ricucci & Siqueira, 2010). A biofilm community is incredibly adaptive and persistent, enabling survival in a hostile environment, while maintaining the ability to express its pathogenicity upon the host (Costerton & Stewart, 1999). A significant feature of biofilms is the ability to resist antimicrobial agents, as bacteria in this community can be 100 to 1000 times more resistant to certain antibiotics compared to their planktonic counterparts (Ceri et al., 1999). Consequently, disruption and removal of biofilms has proven to be challenging and remains an obstacle in endodontic treatment (Siqueira, 2008). Disinfection difficulties are further accentuated in the apical one third due to the limitations of modern instrumentation (Peters, 2004) and the inability of the irrigant to penetrate the narrow regions of the root canal system (Senia et al, 1971). The penetration of an irrigant in to the apical third of the root canal system is dependent on the size of the apical preparation (Falk & Sedgley, 2005; Hsieh et al., 2007), the depth of the irrigating needle (Hsieh et al., 2007; Sedgley et al, 2005), the volume of irrigation (Baker et al 1975; Sedgley et al, 2004), and the diameter of the irrigating needle (Chow, 1983; Hsieh et al, 2007). In addition, it is often difficult for irrigants to penetrate the apical portion of the root canal system due to the vapor lock effect (Tay et al, 2010). Traditional syringe and needle irrigation is relatively inefficient due to the limited mechanical flushing of debris in the apical third (Boutsioukis et al, 2010a), as well as the inability to deliver irrigant more than 1-1.5mm beyond the tip of the

needle (Boutsioukis et al, 2009). For an irrigating solution to be effective it must be in direct contact with the contents of the canal system. Therefore, effective irrigation depends not only on the chemical ability of the irrigants but also upon the ability to deliver the irrigant throughout the entire root canal system, particularly the apical third. Furthermore, the irrigation system should be capable of debriding areas that were inaccessible by mechanical instrumentation, including the fins, lateral canals and isthmi, in a safe manner.

Numerous irrigation delivery systems are available for enhancing the distribution and streaming of irrigants (Goodman et al, 1985; Gu et al, 2009). A key feature among the various systems is the ability to agitate or activate irrigating solutions as agitation of irrigants has been shown to improve the effectiveness of irrigation (Moorer & Wesselink, 1982). One such way to enhance the action of irrigants is by employing the use of ultrasound energy. Previous studies have demonstrated irrigation delivery can be enhanced by using ultrasonic energy (Goodman et al, 1985; Sjögren & Sundqvist, 1987; Archer et al, 1992; Jensen et al, 1999; Lee & Wu, 2004;). However, the efficacy of newer generation irrigation delivery systems to debride and disinfect the root canal has not been thoroughly evaluated. There is promise in these devices, however, further quantification is required and the impact on the outcome of endodontic treatment is still uncertain.

1.1 Outcome of Endodontic Treatment

Successful endodontic outcome requires both clinical and radiographic normalcy. Strindberg incorporated a stringent set of criteria for success and failure based on the presence or absence of periapical rarefaction (Strindberg, 1956). Many of the current criteria for outcome assessment have been adopted from the strict criteria set by Strindberg. Further

to this, the European Society of Endodontic has set forth guidelines regarding outcome that states root-filled teeth should be reviewed radiographically at 1 year and then subsequently as required for up to 4 years to assess whether treatment has been successful (European Society of Endodontology, 2006). Numerous studies have been published that have evaluated the outcome of endodontic treatment in controlled clinical environments. Strindberg's classic study in 1956 evaluated 254 patients with 529 teeth over a 6 year period (Strindberg, 1956). The recall period was between 6 months and 10 years with 97.5% being followed for at least 2 years. The success rate of initial treatment was 91.6% with no initial periapical lesion and 82.4% with an initial periapical lesion. Sjögren looked at the various factors that may affect the outcome of endodontic treatment in (Sjögren et al, 1990) . The follow-up period was 8-10 years with an overall success rate of 91%. In cases where no initial periapical lesion was present the success was 96% and with an initial periapical lesion the success dropped to 86%. In 2003, Phase I of the Toronto Study was published (Friedman et al, 2003). The objective of the Toronto Study project was to prospectively assess the 4- to 6-yr outcome of endodontic treatment performed in a university graduate-clinic environment. Phase I presented an overall healed rate of 81%. The healed rate was significantly higher without apical periodontitis (92%) than with apical periodontitis (74%). The Toronto Study Phase IV, which was pooled with data from Phases I-III, showed an overall healed rate of 86% and similarly, the healed rate varied with the presence or absence of a preoperative periapical radiolucency (93 vs 82%) (Farzaneh et al, 2004; Marquis et al, 2006; de Chevigny et al, 2008). This study also reported that 95% of the teeth remained asymptomatic and functional. The clinical outcome of endodontic treatment of teeth with apical periodontitis was evaluated by Siqueira (Siqueira et al, 2008) . A standardized microbial protocol was utilized with a 1-4

year follow-up period and a combined healed and healing rate of 95% was observed. The conclusion of this study was that high success rates were observed when an evidence-based antimicrobial strategy was used during endodontic treatment of teeth with apical periodontitis.

These controlled clinical studies, many of which are University based, demonstrate success rates as high as 96%. However, epidemiologic studies performed in different countries reveal a different picture with periapical disease present in 35-65% of root canal treated teeth (Eckerbom et al, 1987; De Cleen et al, 1993; De Moor et al, 2000; Kirkevang et al, 2001; Dugas et al, 2003). Evidently, there is a large dichotomy between what is achievable and what is actually observed in regards to endodontic outcome. The large discrepancy may be a function of poor disinfection treatment protocols. Increase in endodontic outcome is directly related to our ability to efficiently, predictably and safely disinfect the root canal system. Effective evidence based treatment protocols provide favorable outcomes and it is unlikely that these protocols are being utilized in the general dentist population.

1.2 A Brief History of Irrigation

With the works of Pasteur, Lister, and Koch, there became a growing acceptance of an association between microorganisms and infection in the 19th century. The establishment of the germ theory of disease was followed by efforts to prevent infection with Koch demonstrating the eradication of bacteria with hypochlorites (Sedgley, 2004). These developments along with the establishment of the Baltimore College of Dental Surgery in 1840, greatly impacted dentistry as the use of broaches and intracanal dressings became more prevalent. The practice of wiping root canals with disinfectants to achieve sterilization was

commonly practiced. The need for frequent syringing of the root canal appears to have been first advocated by Jonathan Taft in 1859, with the purpose of treating the slough or discharge through the tooth (Taft, 1868). Nitrates of silver, creosotes and tannin, or chlorid or sodium were commonly used to wash the innermost portion of the cavity. Willoughby Dayton Miller published a series of papers from 1891-1894 that showed the role of microorganisms in pulpal and periapical disease (Miller, 1891a; 1891b; 1894). Miller's work led to the realization that the root canal treatment required an aseptic approach as he showed a strong association between microorganisms and infections related to teeth. A variety of empirical recommendations on the use of medicaments to clean root canals were made throughout this period (Sedgley, 2004). Arsenic was introduced in 1836 to treat the nerves of teeth. Callahan suggested 20-50% sulfuric acid to help clean and widen the root canal followed by a bicarbonate solution to cause an effervescent reaction and neutralizing the acid (Callahan, 1894). One method involved placing potassium and sodium metals in the root canal resulting in a volatile reaction which purportedly removed necrotic pulps. In a dental medicine manual by Gorgas, treatment for alveolar abscess entailed cleansing of the root canal by injecting chlorid of sodium or hydrogen peroxide, which was followed by sulfuric acid to destroy any remaining tissue in the canal (Gorgas, 1889). G.V. Black advocated the use of medicaments such as oil of cloves, oil of cinnamon, Beechwood Creosote, and Black's 1,2,3 to clean root canals and discouraged the use of stronger antiseptics due to irritation concerns (Black, 1915). Hydrogen peroxide was frequently recommended in the early 1900's with the thought that the effervescence that was created would provide disinfection of the root canal. In 1915, Dakin introduced the use of a 0.5% sodium hypochlorite solution for the irrigation of wounds during World War I (Dakin, 1915). This prompted the introduction

of sodium hypochlorite to endodontics with the earliest published reports by Coolidge and Crane (Coolidge, 1919; Crane, 1920). Walker further recommended the use of sodium hypochlorite in 1936 (Walker, 1936) and this was followed by a classic article from Grossman based on experimental work on root canal irrigation that confirmed the effectiveness of sodium hypochlorite as a pulp tissue solvent (Grossman, 1943). Grossman strongly recommended chlorinated soda alternated with hydrogen peroxide. In describing the technique of irrigation, Grossman stated that mechanical instrumentation should be followed by this irrigation combination to wash out fragments of pulp tissue and dentinal shavings from the root canal. Another significant event was the introduction of chelating agents into endodontics as an aid for the preparation of narrow and calcified root canals in 1957 by Nygaard-Ostby (Nygaard-Østby, 1957). With the establishment of the American Association of Endodontics in 1943, irrigation research has grown with many of Grossman's principle about irrigation still utilized today.

1.3 Endodontic Treatment

1.3.1 Mechanical Preparation of the Root Canal

The main purpose of root canal instrumentation is the mechanical debridement of the root canal system. This involves the removal of vital and necrotic tissue, as well as hard tissue from the root canal system, creation of sufficient space for delivery of irrigants and intracanal medications, preparation of an adequate shape that will allow placement of a high quality obturation material within the confines of the root, avoidance of iatrogenic damage of the root canal system, and prevention of further damage to the periapical region (Haapasalo et al,

2005; Hülsmann et al, 2005). Furthermore, the ultimate biological goal of mechanical instrumentation is the eradication of bacteria from the root canal system, and prevention and treatment of endodontic disease. Root canal preparation instruments and techniques have evolved over time and include the use of manual preparation with stainless handfiles, automated root canal instrumentation, sonic and ultrasonic preparation, the use of nickel-titanium hand and rotary files, and the use of lasers in endodontics.

Numerous studies have been performed on the mechanical reduction of bacteria by instrumentation. Ingle and Zeldow evaluated the role of mechanical instrumentation alone in the reduction of bacteria in the root canal system (Ingle & Zeldow, 1958). Using hand instrumentation with large reamers and irrigation with distilled sterile water, they found 80% of the root canals had a positive culture after the first appointment. At the start of the second appointment 95.4% yielded a positive culture. He noted that the difference between his results and a similar one by Stewart, and concluded the difference was due to the use of sterile water as the irrigant. Stewart reported negative cultures in 76% of the infected teeth after chemomechanical preparation of the root canals using 3% hydrogen peroxide and sodium hypochlorite (Stewart, 1955). Bystrom and Sundqvist, using then state-of-the-art anaerobic bacteriological techniques, were able to demonstrate that mechanical debridement of the canal, while using only sterile saline as an irrigant, was capable of reducing the number of microorganisms by 100-1000 fold (Byström & Sundqvist, 1981). However, despite the multiple appointments, only 53% of the root canals were rendered bacteria-free with a negative culture. Their conclusion was that mechanical instrumentation and irrigation with saline reduced the number of bacteria in the root canal and the supporting action of disinfectants would be necessary for successful removal of the remaining bacteria. Bystrom

and Sundqvist published a succeeding paper and they utilized 0.5% hypochlorite as the irrigant along with mechanical instrumentation (Byström & Sundqvist, 1983). This resulted in 83% of the root canals showing a negative culture and reinforced the limitation of the use of mechanical instrumentation alone for disinfection. Ørstavik published a clinical study demonstrating the effects of mechanical instrumentation with saline as the irrigant. (Ørstavik et al, 1991). Although, there was a reduction in the bacterial load of the root canals, he concluded that the mechanical instrumentation was relatively inefficient. He did note however, that there was increased bacterial reduction with larger apical sizes. Wu compared 3 instrumentation techniques in curved mesio-buccal canals of mandibular molars (Wu & Wesselink, 1995). He concluded that none of the techniques were able to completely debride the apical portion, however the technique that created larger apical sizes had less debris remaining in the apical third. Similarly, Siqueira compared 5 instrumentation techniques and the apical third of the root canals was assessed using histological examination (Siqueira et al., 1997). He demonstrated that regardless of the technique used, complete debridement of the root canal system was not observed.

The introduction of Nickel Titanium Rotary instrumentation was a significant advancement as it offered several advantages over traditional hand instrumentation to facilitate the cleaning and shaping process such as faster canal preparation, less debris extrusion, less transportation, centering ability, and reduced iatrogenic errors (Bergmans et al, 2001). Dalton's clinical study of 48 teeth with apical periodontitis measured the bacterial reduction using either stainless steel handfiles or nickel-titanium rotary instrumentation (Profile .04 taper), with sterile saline as the irrigant (Dalton et al, 1998). Only 28% of the samples were bacteria free, however, no significant difference in intracanal bacterial reduction was

detected between hand and rotary instrumentation. Increasing bacterial reduction with increasing instrument size, regardless of the file type, was also observed. Siqueira also evaluated reduction of the bacterial population in the root canal system by the mechanical action of instrumentation and irrigation with sterile saline (Siqueira et al, 1999). Canals inoculated with an *Enterococcus faecalis* suspension were cleaned and shaped using hand Ni-Ti Flex files, Greater Taper files, and Profile 0.06 taper series 29 rotary instruments. There was no significant difference among the three techniques in bacterial reduction. Teeth that were enlarged to size 40 did have an increased bacterial reduction. Siqueira concluded that mechanical instrumentation is insufficient to completely eradicate root canal infection and the use of irrigation solutions possessing antibacterial properties is essential to proper disinfection. In spite of the advances in mechanical instrumentation with the use of nickel titanium rotary instruments, the studies did not show an increase in disinfection. Based on the findings of these studies on the mechanical preparation of root canals, it is evident that mechanical instrumentation, regardless of technique, with saline is insufficient to predictably disinfect the root canal system and supplementation with a strong antimicrobial irrigating solution is highly necessary.

1.3.2 The Importance of Chemomechanical Preparation

The main goal of chemomechanical preparation is to clean and disinfect the entire root canal system by eliminating bacteria as well as any sources of nutrient supply, such as the tissue remnants. Cleaning and disinfecting procedures are highly dependent on the mechanical and chemical effects of the irrigants. Regardless of the type of irrigant used, there is a significant bacterial reduction in the root canals just by the mechanical effects of

irrigation (Siqueira et al, 1999). Irrigants work mechanically, via the flow and backflow of the solutions, to loosen debris and bacteria and flush them from the root canal system. The antibacterial effects of an irrigant will enhance bacterial reduction throughout the root canal system and especially in areas inaccessible to mechanical debridement. Therefore, chemomechanical preparation will remove bacteria from the root canal by the mechanical action of instruments, the flow and movement of irrigant solutions, as well as the antibacterial effects of irrigants. Svec and Harrison evaluated the effectiveness of chemomechanical preparation with normal saline solution against a combination of 5.25% sodium hypochlorite and 3% hydrogen peroxide in extracted single rooted teeth (Svec & Harrison, 1977). They concluded that the sodium hypochlorite and hydrogen peroxide combination was more effective at debriding the canals in the apical 3 mm, however, neither solution was able to render the canals completely free of tissue debris. Based on the recommendations of their earlier study, Byström and Sundqvist compared the antibacterial properties of 0.5% sodium hypochlorite and sterile saline irrigants in infected root canals (Byström & Sundqvist, 1983). The use of sodium hypochlorite irrigation coupled with mechanical instrumentation rendered 80% of the canals bacteria-free after the fifth and final appointment, while saline irrigation was only able to render 53% of the canals bacteria free. In 1985, Bystrom compared the antibacterial effects of 0.5%, 5% sodium hypochlorite and a combination of 5% sodium hypochlorite and 17% EDTA (Bystrom & Sundqvist, 1985). There was no difference between the two concentrations of sodium hypochlorite, however the 5% sodium hypochlorite with the EDTA was the most effective, but attaining complete eradication of the microorganisms was still unachievable. Siqueira compared the effects of instrumentation and 3 of different concentrations of sodium hypochlorite (1%, 2.5%, and

5.25%) against saline on intracanal bacterial reduction (Siqueira et al, 2000). There was a considerable bacterial reduction with the use of different sodium hypochlorite concentrations compared to saline in the root canals. There was no difference between the 3 sodium hypochlorite groups. The results of this study suggest that regular exchange and the use of large amounts of irrigant should maintain the antibacterial effectiveness of the sodium hypochlorite, compensating for the effects of concentration. Nevertheless, bacteria were never completely eliminated from the root canals. Shuping evaluated the extent of bacterial reduction with nickel-titanium rotary instrumentation and 1.25% sodium hypochlorite irrigation (Shuping et al, 2000). The study also incorporated larger apical sizes in the mechanical instrumentation protocol. There was a significantly greater reduction of bacteria when sodium hypochlorite was used as an irrigant, compared with sterile saline. After instrumentation with sodium hypochlorite as the irrigant, 61.9% of canals were rendered free of bacteria. However, this was increased to 92.5% with the use of calcium hydroxide as an intra-canal medicament. Peters evaluated the effect of instrumentation with 2% sodium hypochlorite on the fate of intracanal bacteria on teeth with necrotic pulps and periapical lesions and showed 76% of the teeth had a negative culture after cleaning and disinfection in the first visit (Peters et al, 2002). However, in this study there was not further reduction of negative cultures with a 4-week application of calcium hydroxide. McGurkin-Smith's clinical study of teeth with apical periodontitis evaluated the bacterial reduction using nickel-titanium rotary files and a strict irrigation protocol utilizing 5.25% sodium hypochlorite and 17% EDTA (McGurkin-Smith et al, 2005). Following this protocol, 47% of the teeth did not culture bacteria after the instrumentation and irrigation protocol. However, this was increased to 86% after a one-week treatment of calcium hydroxide. It was concluded the

protocol significantly reduced the number of bacteria in the canal but failed to render the canal bacteria free in more than half of the cases and large apical preparations removed more bacteria than small apical preparations. Siqueira's study in 2007 assessed the effect of chemomechanical preparation with 2.5% sodium hypochlorite and an intracanal medication (Siqueira et al, 2007). A significant reduction in the number of intracanal canal bacteria following the protocol was observed. No cultivable bacteria were isolated from 54.5% of the canals after instrumentation with hand NiTi files and irrigation with 2.5% sodium hypochlorite. This was further increased to 81.8% after a 7-day application of calcium hydroxide. However, Siqueira concluded that despite the reduction in bacteria, some cases still harbored bacteria after chemomechanical preparation and more effective strategies need to be developed to predictably render canals free of bacteria. Altogether, the studies show the inability to achieve bacteria free root canal systems with chemomechanical preparation, and puts into question outcome of endodontic treatment, as the success is dependent upon achieving complete elimination of bacteria from the root canal system before obturation (Sjögren et al, 1997).

1.3.3 Treatment Considerations

As mentioned, mechanical preparation has its limitations, as it is unable to significantly reduce the bacteria within the canal. Despite advances in mechanical preparation with nickel titanium rotary instrumentation, much of the root canal space remains untouched by instruments and can harbor bacteria after seemingly adequate mechanical preparation. The use of micro-computed tomography technology has aided in quantifying the effects of instrumentation on the root canal walls. Peters' study in 2001 compared the effects of 4

instrumentation techniques on the changes in root canal geometry of maxillary molars. He demonstrated that all 4 instrumentation techniques left 35% or more of the canals' surface area unchanged (Peters et al, 2001b). In fact, the palatal canals of maxillary molars had as high as 57% of the canal walls untouched by instruments (Peters et al, 2001a). Peters evaluated the effect of Protaper rotary instruments on the canal geometry of maxillary molars and found that 33-49% of the canal walls were left untouched (Peters et al, 2003). Paque compared the effect of 4 instrumentation techniques on the prepared surfaces of oval-shaped distal canals of mandibular molars and showed that showed untreated areas of the canal ranged from 59.6% to 79.9% for the total canal length and 65.2% to 74.7% for the apical canal portion, respectively (Paque et al, 2010). These findings reinforce the understanding of the limitations of mechanical preparation in the complexities of the root canal system, especially in the apical 4 mm, and stress the importance of chemical disinfection with antimicrobial irrigants.

Conversely, when root canals are instrumented a layer of material composed of dentine, remnants of pulp tissue and odontoblastic processes, and bacteria are always formed on the root canal wall (Şen et al, 1995). This layer is referred to as the smear layer and was first described by McComb in 1975 (McComb & Smith, 1975). McComb recognized, with the use of scanning electron microscopy, that standard instrumentation techniques produced this layer on root canal walls. This study examined various combinations of irrigants and demonstrated that the use of EDTA and REDTA following instrumentation produced the canals that were the most smear and debris free. Mader showed that the smear layer was 1-2 microns thick and that it had two components: a friable superficial layer and smeared layer that was packed into the dentinal tubules up to 40 microns in depth (Mader et al, 1984).

Several studies have shown that the most effective means to remove the smear layer is a combination of sodium hypochlorite and EDTA (Baumgartner & Mader, 1987; Goldman et al, 1982; Yamada et al, 1983). There are conflicting reports regarding the decision to remove the smear layer. This layer covers the instrumented walls and may prevent the penetration of irrigants and intracanal medicaments into the dentinal tubules and interfere with the close adaptation of root filling materials to canal walls. However, the data appears to point in the direction of smear layer removal as this can facilitate more thorough disinfection of the root canal system and better adaptation of materials to the canal walls (Violich & Chandler, 2010).

1.3.4 Desired Properties of Irrigants

Ideally, root canal irrigants should:

- Have a broad antimicrobial spectrum and high efficacy against high anaerobic and facultative bacteria organized into biofilms
- Dissolve organic matter such as necrotic pulp tissue
- Act as a lubricant in the root canal
- Mechanical flush debris from the root canal
- Inactivate endotoxin
- Prevent the formation of a smear layer during instrumentation or dissolve the latter once it has formed
- Be systemically nontoxic, non-caustic to periodontal tissues and have little potential to cause an anaphylactic reaction

Unfortunately, one such irrigant does not exist therefore the combination use of various irrigants in a proper sequence is essential to achieving thorough disinfection of the root canal system (Zehnder, 2006; Haapasalo et al, 2010).

1.3.5 Sodium Hypochlorite

Sodium hypochlorite is the most widely used irrigation solution in endodontics today mainly due to its marked antimicrobial effect and tissue dissolving ability (Zehnder, 2006). In addition, it is cheap, readily available, and has a long-lasting shelf life. Sodium hypochlorite is a strong base with a pH >11 and is commonly used in concentrations between 0.5-6%. Sodium hypochlorite dissociates in water into Na⁺ and the hypochlorite ion (OCl⁻), establishing equilibrium with hypochlorous acid (HOCl), as shown by the following reaction:



At a neutral or acidic pH chlorine exists predominantly as HOCl and at pH 9 or above, OCl⁻ is the dominant form. Hypochlorous acid is the form that is responsible for the antimicrobial activity and it exerts its germicidal effect by oxidative action on sulphhydryl groups of essential bacterial enzymes. The inhibition of these enzymes results in interference with metabolic functions, which then presumably result in the death of these bacteria. The antimicrobial effectiveness of sodium hypochlorite is also based on its high pH due to the hydroxyl ions action, which is similar to the mechanism of action of calcium hydroxide.

The high pH of sodium hypochlorite interferes in the cytoplasmic membrane integrity with an irreversible enzymatic inhibition, biosynthetic alterations in cellular metabolism and phospholipid degradation (Estrela et al., 2002).

Estrela proposed that 3 chemical reactions can occur between sodium hypochlorite and organic tissue (Estrela et al., 2002). The first is a saponification reaction in which fatty acids are broken down to soap and glycerol, which decreases surface tension of the liquid. A neutralization reaction can occur that will break down amino acids to form salt and water, and causes an increase in pH by the release of hydroxyl ions. The last reaction that may occur is a chloramination reaction, where hypochlorous acid will react with organic tissue to form chloramines that interfere in cell metabolism of bacteria. Therefore, the antimicrobial activity exhibited by sodium hypochlorite is due to formation of hypochlorous acid, hydroxyl ions and the chloramines, which act on the bacterial essential enzymatic sites promoting irreversible inactivation. The breakdown of organic tissue can be accounted for by the saponification reaction of lipids and fatty acids (Mohammadi, 2008).

1.3.5.1 Tissue Dissolving Effects

The tissue dissolving abilities of sodium hypochlorite have been well studied. Grossman showed the ability of sodium hypochlorite to dissolve necrotic tissue and recommended its use as part of his irrigation protocol (Grossman, 1941). Senia evaluated the tissue dissolving ability of 5.25% sodium hypochlorite compared to saline in extracted mesial roots of mandibular molars (Senia et al, 1971). After histologic preparation, he showed the sodium hypochlorite was more effective than saline but the effects were limited in the apical 3mm of the root canals. He concluded maximum contact with the tissue was required and this may

have been limited in the small apical areas of the mesial roots. Rosenfeld also showed the tissue dissolution effect of sodium hypochlorite on intact vital pulps, and also concluded that the effects were limited in the apical thirds of the teeth (Rosenfeld et al, 1978). Hand compared the tissue dissolution properties of various concentrations of sodium hypochlorite on necrotic tissue in rat pulps (Hand & Smith, 1978). 5.25% sodium hypochlorite was shown to be significantly more effective as a tissue solvent than any other of the tested solutions. Abou-Rass studied the effects of varying concentrations and temperature on the tissue dissolution properties of sodium hypochlorite (Abou-Rass & Oglesby, 1981). In addition, they evaluated the influence of the tissue condition (fresh, fixed, or necrotic) on dissolution effectiveness. He concluded that the higher concentration was the most effective, heating the solution was more effective regardless of concentration, and that the dissolution was the greatest on fresh tissue. Moorer and Wesselink showed that tissue dissolution was dependent on three factors: frequency of agitation, amount of organic matter in relation to the amount of irrigant in the system and surface area of tissue that was available (Moorer & Wesselink, 1982). Naenni evaluated the soft tissue dissolution ability of various irrigants commonly used in endodontics and found that only 1% sodium hypochlorite was able to dissolve major amounts of tissue (Naenni et al, 2004). Stojicic evaluated the effect of concentration, temperature and agitation on the tissue dissolution ability of sodium hypochlorite (Stojicic et al, 2010). In addition, a hypochlorite product with an added surface active agent was compared with conventional hypochlorite solutions. This study concluded that an increase in concentration and temperature of sodium hypochlorite greatly increased its efficacy in tissue dissolution. Also, agitation of the hypochlorite solution, preferably continuous, resulted in a marked increase in the effect of the hypochlorite. The sodium hypochlorite product with

added surface active agent was the most effective in tissue dissolution at all concentrations and temperatures.

1.3.5.2 Antibacterial Effect

Sodium hypochlorite was shown to be a powerful germicide since its introduction into the medical field by Dakin (Dakin, 1915). In 1970, Shih conducted a laboratory study to assess the antibacterial efficiency of sodium hypochlorite as a root canal irrigant (Shih et al, 1970). This study looked at the effect of the 5.25% sodium hypochlorite on *Streptococcus faecalis* and *Staphylococcus Aureus*. The study concluded that it is necessary to use 5.25 % sodium hypochlorite to obtain an immediate sterilizing effect in the infected root canals of extracted human teeth. Siqueira evaluated the antibacterial effect of endodontic irrigants against four black-pigmented Gram- negative anaerobes and four facultative anaerobic bacteria by means of the agar diffusion test (Siqueira et al, 1998). He compared various concentrations of sodium hypochlorite and chlorhexidine, as well as citric acid and EDTA. The 4% sodium hypochlorite solution provided the largest average zone of bacterial inhibition in this study when compared to all the other solutions. Berber compared the efficacy of 0.5%, 2.5% and 5.25% sodium hypochlorite as intracanal irrigants associated with hand and rotary instrumentation techniques against *Enterococcus faecalis* within root canals and dentinal tubules (Berber et al, 2006). Extracted human premolar teeth were infected with *Enterococcus faecalis* and subjected to various combinations of instrumentation and irrigation. After analysis, the results of the present study suggest that 5.25% sodium hypochlorite has a greater antibacterial activity inside the dentinal tubules infected with *Enterococcus faecalis* than the other concentrations tested. Clegg evaluated the effectiveness

of different concentrations of sodium hypochlorite and several other commonly used endodontic irrigants on the eradication of biofilms from dentin sections (Clegg et al, 2006). He concluded that 6% sodium hypochlorite was the only irrigant capable of both eliminating the bacteria and physically removing the biofilm.

1.3.5.3 Limitations of Sodium Hypochlorite

There is no consensus on the safest concentration of sodium hypochlorite to use in endodontics as the range is 0.5-6%. Spangberg evaluated the cytotoxicity and antibacterial effectiveness of sodium hypochlorite and recommended the use of a 0.5% concentration (Spangberg et al, 1973). This concentration demonstrated an optimal level of cell compatibility while dissolving necrotic tissue along with retaining an adequate antimicrobial effectiveness. Safety is an important consideration as complications with its use can occur. The use of sodium hypochlorite can result in accidental injection beyond the root apex which can cause violent tissue reactions characterized by pain, swelling, hemorrhage, and in some cases the development of secondary infection and paresthesia (Mohammadi, 2008). Therefore, extreme care should be used when using sodium hypochlorite during endodontic irrigation.

Sodium hypochlorite cannot dissolve inorganic dentin particles, therefore the formation of a smear layer during instrumentation cannot be prevented (McComb & Smith, 1975). The use of a chelating solution in conjunction with sodium hypochlorite is recommended to remove the smear layer that is formed during instrumentation (Violich & Chandler, 2010). Sodium hypochlorite has shown to have its effectiveness reduced in the presence of dentin and other organic compounds within the root canal system. Haapasalo demonstrated a reduction in the

effectiveness of sodium hypochlorite against *Enterococcus faecalis* in the presence of dentin powder (Haapasalo et al, 2000). Pappen demonstrated that the antimicrobial activity of sodium hypochlorite against various microbes was inhibited by the presence of bovine serum albumin (Pappen et al, 2010) . These findings may explain the poorer results obtained from in vivo studies compared to in vitro ones.

1.3.6 EDTA

EDTA is a common chelating solution that reacts with the calcium ions in dentine and forms soluble calcium chelates. It is available in a paste or liquid form and is readily used in endodontics, however, it does not possess any antibacterial properties (Zehnder, 2006). The disodium salt of EDTA is most commonly used as a neutralized 17% solution with a pH of 7, although varying concentrations and different formulations have been used in endodontics (Violich & Chandler, 2010). EDTA is effective in removing the smear layer that is created after mechanical instrumentation, as sodium hypochlorite by itself is unable to remove the smear layer (Yamada et al., 1983). The removal of the inorganic debris by EDTA allows sodium hypochlorite to access and dissolve any remaining organic debris. This is demonstrated in a study by Baumgartner in which he evaluated 4 irrigation regimens for debridement and found that the combination of sodium hypochlorite and EDTA used alternately completely removed the smear layer from the instrumented root canal surfaces (Baumgartner & Mader, 1987). Due to concerns regarding the strong demineralizing effects of EDTA, the effect on the properties of dentin and the clinical implications are not fully understood. Calt and Serper examined the time dependent effect of EDTA on smear layer removal as excessive erosive effects were observed with dissolution of peritubular and

intertubular dentin in other studies (Calt & Serper, 2002). Based on their findings a 1-minute application of EDTA was recommended to remove smear layer as application for longer than this would lead to excessive erosion and potentially weaken the tooth. Mello evaluated the influence of the volume of 17% EDTA on smear layer removal in different parts of the tooth (Mello et al, 2008). The results of this study showed that 5 mL of 17% EDTA per canal provided good smear layer removal, with root canal walls free of debris and mostly open dentinal tubules. Mello also evaluated the final rinse technique on the ability to remove smear layer using 17% EDTA (Mello et al, 2010). He compared a continuous rinse technique against a rinse and soak technique in extracted teeth. The study concluded that a continuous rinse with 5 mL of 17% EDTA for 3 minutes was more efficient in the smear layer removal from all areas of root canal walls.

1.4 The Dynamics of Irrigation

Irrigation and the irrigant accomplish multiple roles in the various phases of root canal preparation with the objective being mechanical and chemical cleaning of the entire root canal system. The mechanical action involves flushing of pulp tissue, bacteria (planktonic or biofilms), dentin debris and smear layer out of the root canal system, the creation of effective flow to disperse the irrigant in the root canal system, reduction of instrument friction during preparation, and disruption of biofilm from the root canal wall. The chemical action entails dissolution and inactivation of pulp tissue, bacteria (planktonic or biofilm), dentin debris and smear layer in the root canal system, while limiting cytotoxic action to the host tissues. Effective irrigation is dependent upon 2 factors, the irrigant and the irrigant delivery system. Irrigants have been previously discussed and the evidence shows that the currently used

irrigant regimens are effective when they are brought into direct contact with the desired surfaces (Zehnder, 2006). The method of irrigation delivery is a key determining factor in the irrigation dynamics within the root canal system, however, irrigation dynamics is not well understood. Irrigation dynamics involves the flow patterns, velocity, penetration and the exchange of irrigants within the root canal system, as well as the forces created. The flow created within the root canal system is directed towards the apical region as well as the lateral walls of the root canal. The velocity of the irrigant flow will determine whether the flow is laminar or turbulent in nature, and the forces that are created are responsible for the mechanical effects of irrigation. In addition, these forces will determine the extent of the penetration and exchange of the irrigant within the root canal and the chemical effects of the irrigant will be dependent upon this. Therefore, recognition of the importance of irrigation dynamics is essential as even the most powerful irrigant will be of no use if it cannot penetrate the apical portions of the root canal.

1.4.1 Apical Preparation Size and Penetration of Irrigants

Early studies by Senia recognized the limitations of irrigation as they reported the effectiveness of the irrigant was limited in the apical 3 mm of the teeth (Senia et al, 1971). Chlorox was able to dissolve tissue effectively only at the 5mm level, compared to saline, therefore the delivery of the irrigant was poor in the apical 3mm. Salzgeber's in vivo study looked at the penetration of irrigating solutions with the use of radiopaque dye (Salzgeber & Brilliant, 1977). He showed penetration of the irrigant to the apex in vital and necrotic teeth when they were prepared to size 35 and irrigated with a 23-gauge needle open-ended needle. This was achieved without forceful pressure during the irrigation. Ram also assessed the

delivery of irrigant throughout the root canal system in extracted teeth using a radiopaque dye and determined that the key factor was the apical preparation (Ram, 1977). He stated that effective irrigation would not occur unless the apical preparation was size 40 or greater, as this would allow penetration of the needle to the apex to facilitate better cleaning and exchange of the irrigant. Falk evaluated the mechanical efficacy of irrigation in the removal of intracanal bacterial and determined that the efficacy of irrigation was significantly improved with a size 60 apical preparation compared to size 36, however, size 77 offered no additional benefit (Falk & Sedgley, 2005). In a more recent study, Khademi evaluated the minimal apical size required for effective irrigant penetration and elimination of debris and smear layer in apical region of extracted teeth (Khademi et al, 2006). He concluded that an apical size of 30 with a taper of .06 was effective for debris and smear removal in the apical area. Hsieh used a thermal image analysis system to assess various factors on the flow distribution of irrigants in the prepared root canals (Hsieh et al, 2007). The extracted teeth were prepared to varying apical sizes and irrigated with varying size irrigating needles, which were placed at varying depths. The study showed that the flow distribution was significantly influenced by the size of the apical preparation. Boutsoukis evaluated the effect of apical preparation size on irrigant flow inside a root canal during final irrigation using a Computational Fluid Dynamics model (Boutsoukis et al, 2010a). He concluded that apical preparation size was found to affect the extent of irrigant replacement, the shear stress on the canal wall and the pressure at the apical foramen. In addition, root canal enlargement to sizes larger than 25 improved the performance of syringe irrigation.

1.4.2 Depth of Needle Placement and Needle Size

Abou-Rass evaluated the effectiveness of different irrigation techniques on the removal of dentinal debris from root canals (Abou-Rass & Piccinino, 1982). The study used extracted teeth and examined the influence of differing needle sizes, 2 different apical preparations (size 25 and 40), and different irrigant combinations on the removal of a radiopaque medium from root canals. He concluded that the needle delivering the solution must come in close proximity to the apex to remove debris, a size 25 apical preparation could be flushed of debris if there was adequate taper in the preparation to allow needle placement, and that 30-gauge needles were more effective than 23-gauge needles. Chow's in vitro study in 1983 assessed the mechanical effect of irrigation in root canals (Chow, 1983). The experiments looked at several variables including needle size, depth of placement, canal size (test tube size), and flushing and displacement of artificial particles. He concluded that the effectiveness of irrigation appears to be dependent upon the depth of the insertion of the needle. In addition, smaller size needles were more effective than larger ones, as the finer needles were able to reach the apex without binding and remove particles, which facilitated cleaning. In Ram's study, he also noted that smaller needles appear to be more effective as they penetrate further into the canal and promote better exchange and cleaning (Ram, 1977). An in vitro study by Kahn, evaluated the efficacy of various irrigating devices in clearing dye from plastic blocks (Kahn et al, 1995). Kahn concluded that the 30 gauge Max-i-probe (Dentsply International, New York, USA) irrigating needles were significantly more effective in dye clearance due to the needle design and ability to penetrate further in smaller canal preparations. Sedgley assessed the influence of needle depth in prepared root canals by bacterial reduction (Sedgley et al, 2005). The needle was placed either 1mm or 5mm from

working length and irrigated with 2 different volumes of non-antimicrobial irrigant. The mechanical efficacy of 6 mL of irrigant in reducing intracanal bacteria was significantly greater when delivered 1 mm compared with 5 mm from working length. Hsieh's study in 2007, which assessed apical preparation size, also evaluated needle size and depth of placement from working length (Hsieh et al, 2007). The study concluded that the flow distribution of root canal irrigation was adversely affected by needles of larger diameter and by increased distance of the needle from the working length.

1.4.3 Influence of Canal Taper

The influence of the taper of the root canal preparation on irrigation dynamics has not been extensively examined. Nickel-Titanium rotary file systems are now incorporating multiple tapers into the design and this may influence the efficacy of root canal irrigation. Abou-Rass demonstrated that an increased coronal taper would increase irrigation efficacy in teeth that were only prepared to size 25 by allowing further penetration of the irrigating needle (Abou-Rass & Piccinino, 1982). Albrecht examined the effect of taper, with 2 different apical sizes, on the ability of irrigant to remove debris from the root canal (Albrecht et al, 2004). The tapers tested were .04, .06, .08, and .10 in the Profile GT system and it was determined when a taper of .10 can be produced at the apical extent of the canal, there was no difference in debris removal between the two preparations sizes. They speculated that this could be due to the increased penetration of the irrigation needle and subsequent improvement in the effectiveness of irrigation. Huang evaluated the influence of canal dimensions and irrigation variables on the efficacy of irrigation using a bio-molecular film model and concluded that the apical size and taper of the canal preparation had a significant influence on the outcome

of irrigation (Huang et al, 2008) . Bronnec assessed the irrigant penetration and renewal in an ex vivo model and found that the 10% taper allowed greater penetration of the irrigating needle than the 7% taper and significantly increased the solution penetration (Bronnec et al, 2010).

1.4.4 Volume of Irrigant

The influence of the volume of irrigant on irrigation efficacy has been evaluated and appears to show a positive effect. An early study by Baker examined the effectiveness of various solutions used to irrigate and clean root canals by scanning electron microscopy (Baker et al, 1975). There was no evident difference in the ability of the various agents to debride root canals and the removal of debris appeared to be a function of quantity of irrigating solution, not the type of solution. Sedgley used real-time imaging to observe the effect of 3 and 6 ml of irrigating solution on bioluminescent bacteria in prepared root canals (Sedgley et al, 2004). This novel method demonstrated a significant difference in bacterial reduction with 6 ml of irrigant compared to 3 ml. Bronnec's study, which assessed irrigant penetration renewal, showed that the volume of irrigant used had a significant effect on irrigation penetration, as measured by clearance of radiopaque dye from the curved mesial roots of extracted mandibular molars (Bronnec et al, 2010).

1.4.5 Needle Type and Design

The impact of varying needle designs on irrigation effectiveness has not been widely evaluated in the literature. Early studies utilized only open-ended hypodermic needles and often the effect of the needle was not examined. As variations in needle designs were

introduced, studies were performed to assess their influence, however the evaluation of the effect was too macroscopic and many confounding factors existed (Goldman et al, 1979; Sinanan et al, 1983). Recently, a Computational Fluid Dynamics (CFD) model was proposed for the evaluation of irrigant flow in the root canal system (Boutsioukis et al, 2009). This model provided information in regards to the velocity field, shear stress, and pressure in areas that could not be performed by conventional experiments. Boutsioukis used this model to evaluate the effect of needle tip design on the irrigant flow inside a prepared root canal during final irrigation (Boutsioukis et al, 2010b). The study evaluated 6 types of needle design and found differences in the irrigant flow. The open-ended needle design had increased irrigant exchange in front of the needle and towards the apex compared to the closed-ended needle. However, the open-ended needles created more apical pressure, which may be a potential safety concern, due to apical extrusion of irrigant. The close-ended side venting needles created more shear stress on the walls that were adjacent to the opening, and this may be advantageous in the removal of debris and biofilms from the root canal walls. In a similar study, Shen evaluated the effect of needle tip design on irrigant flow pattern via a CFD model (Shen et al, 2010). 4 needle designs were compared: notched, side venting close-ended, side-venting open-ended, and a beveled needle. The irrigation needle tip design influences flow pattern, flow velocity, and apical wall pressure. The apical pressure was highest with the beveled needle and lowest with the side-venting needles.

1.5 Current Limitations in Irrigation

Conventional syringe irrigation with needles is widely utilized in root canal treatment. It is simple, cheap, and easily performed. However, several limitations exist with this technique.

The complex anatomy severely limits the ability of the irrigant to penetrate within the confines of the root canal system. The mechanical flushing action created by the conventional hand-held syringe is relatively weak. The velocity of the irrigant is very high in the lumen of the needle but once it passes out the opening, the velocity drastically decreases in the open area. Consequently, the attenuated irrigant flow has limited effects apically and minimal dislodging forces on the root canal walls (Shen et al, 2010). There exists a stagnation plane or dead water zone in which the irrigant cannot pass beyond after it exits the needle (Gulabivala et al, 2010). The penetration of irrigant was not much beyond the needle tip, and the region apical to this was undisturbed (Ram, 1977; Chow, 1983). Boutsoukis and Shen both demonstrated, with a 30 gauge side-venting needle, the irrigant did not reach further than 1-1.5 mm apically during irrigation (Boutsoukis et al, 2009; Shen et al, 2010). The root canal behaves as a closed-end channel that causes gas entrapment at its closed end. Consequently, it is often difficult for the irrigant to reach the apical region of the root canal due to this vapor lock effect, which was confirmed in the root canal system by Tay (Tay et al, 2010). Chow stated that “ For the solution to be mechanically effective in removing all the particles, it has to: (a) reach the apex; (b) create a current or force; and (c) carry the particles away (Chow, 1983). This seemingly simple goal is not consistently achieved with syringe and needle irrigation and the literature has consistently shown that syringe irrigation, when used in combination with mechanical instrumentation, fails to thoroughly eliminate the bacteria, dentinal debris, and tissue remnants from the root canal system. Therefore, there has been a large-scale effort to overcome these limitations by enhancing the mass dispersal of irrigants with various methods.

1.6 Ultrasound Energy

Ultrasound refers to a cyclic sound pressure wave with a frequency greater than that of the upper limit human hearing, which is 20 kHz or 20000 cycles/second. The production of ultrasound is used in many different fields, typically to penetrate a medium and reveal details about the inner composition or provide focused energy. Common medical uses are in areas such as diagnostic imaging and physiotherapy. Ultrasound waves are produced by the conversion of one form of energy (usually electrical) to sound waves by transduction of the energy. There are two methods to produce ultrasound energy, magnetostriction and the piezoelectric principle. Magnetostriction converts electromagnetic energy into mechanical energy. Within a handpiece, a stack of magnetostrictive metal strips is subjected to a standing and alternating magnetic field, which results in the production of vibrations from the handpiece (Mozo et al, 2012). This type of unit creates a figure eight (elliptical) motion, which is not ideal for endodontic purposes. In addition, magnetostriction generates heat and the units will require adequate cooling. The piezoelectric principle relies on the deformation of a crystal due to the application of an electrical charge. When the crystal deforms, it goes into mechanical oscillation without producing heat. These units produce a linear motion that is more suited for endodontics. The piezoelectric units also produce more cycles per second than the magnetostrictive counterparts, 40 kHz compared to 24 kHz (Plotino et al, 2007).

1.6.1 History of Ultrasonics in Dentistry

The age of ultrasonics in dentistry officially began in November 1952 when an ultrasonic industrial impact grinder was experimentally used to drill extracted teeth (Catuna, 1953).

Catuna reported on the potential use of ultrasonics for cavity preparation and one year later Oman and Applebaum reported on the successful use of an ultrasonic device for cavity preparation in the teeth of patients at Columbia University (Oman & Applebaum, 1954). These units were magnetoconstrictive and worked by vibrating a tool that prepared cavity preparations with the use of an abrasive slurry (Balamuth, 1963). Over the next 3 years, numerous reports appeared in the literature presenting the advantages of ultrasonic cavity preparation (Postle, 1958). However, ultrasonic cavity preparation never became popular due to the inconvenient use of the abrasive slurry and the relatively low cutting speed. The introduction of the high speed rotary drill in 1957 ended the use of ultrasonics for cavity preparation, although it continued to be used in periodontal applications (Street, 1959). The application of ultrasonics for endodontic treatment was first introduced by Richman in 1957 (Richman, 1957). He used an ultrasonic dental unit with a special root canal attachment to open, enlarge, and clean out the contents of the root canal before filling. The special attachment allowed the use of various sizes of broaches, reamers and files to transmit the mechanical vibrations to the root canal. In addition, an ultrasonic chisel attachment allowed apical surgery to be performed in an efficient and gentle manner.

1.6.2 Ultrasonics in Endodontics

After Richman first introduced ultrasonics into endodontics, there was no reported literature until 1976 when Martin demonstrated the bactericidal effects of ultrasonics in extracted teeth (Martin, 1976). He inoculated sterile, prepared molars with 4 different test organisms that were frequently cultured from root canals during endodontic treatment. The goal was to determine quantitatively the bactericidal efficiency of ultrasonics when used with endodontic

irrigants. The study showed that ultrasonics with a neutral phosphate buffered solution had a reducing effect on the bacteria but coupling it with a antibacterial agent led to more efficient disinfection of the root canal system. This was described as a sonosynergistic system for endodontic irrigation as the combined effects of ultrasonics and bactericidal irrigants were shown to be effective in achieving disinfection and ultimately increase endodontic success. Based on previous studies in oral surgery, Martin postulated that ultrasound lavage would create waves that would force the solution into all the complexities of a root canal system. He stated that the chemical effects of ultrasonics are based upon bonding, dissociation effects, activation of radicals and oxidation. In addition, he noted that the physical biologic aspects of ultrasonics were produced by cavitation of the solution (Martin, 1976). Based on this finding, Martin and Cunningham further explored the use of ultrasound in root canal debridement. In 1980, Martin attached K-type files to an ultrasonic unit to facilitate the instrumentation of the root canal. Extracted teeth were prepared by either hand filing or by the K-files attached to the ultrasonic source. When compared against hand instrumentation of root canal dentine, the ultrasonically powered K-type file was found to be superior to hand filed in total dentin removal (Martin et al, 1980b). The results of this study indicate that ultrasonic energizing of a K type file may have application in endodontics for removal of dentin from the root canal. This study was repeated but diamond endodontic files and K-type files were compared for their ability to remove dentin when powered both by hand and by ultrasound (Martin et al, 1980a). The diamond files were significantly superior dentin-removing instruments, especially when energized by ultrasound. In a later study, Cunningham used eleven pairs of extracted teeth and compared hand instrumentation with ultrasonic instrumentation with a size 15 K-file (Cunningham et al, 1982). The irrigant was

2.5% sodium hypochlorite and the instrumentation time was 3 minutes for both methods. Histological examination of the apical area revealed significantly more debris removal with the ultrasonic technique compared to hand filing. In a similar study, Cunningham used a scanning electron microscope to compare the chemomechanical debridement of the root canal surface by hand filing and the endosonic ultrasonic technique (Cunningham & Martin, 1982). The study concluded that the ultrasonically prepared specimens were significantly cleaner, and the smear layer was greatly reduced. Martin also examined the effect of the ultrasonic technique on the amount of root canal debris extruded (Martin & Cunningham, 1982). The study used 38 extracted teeth and compared the effect of ultrasound preparation against hand preparation on debris extrusion. Martin concluded that whether the teeth were prepared within the confines of the root canal or overinstrumented, the ultrasonic technique produced significantly less extruded material than did hand filing.

The series of studies by Martin and Cunningham, demonstrating the superiority of ultrasound debridement, led to an increasing popularity in their technique. The result of their research and clinical success led to the advent of what they termed “endosonic endodontics-an ultrasonic synergistic system”. Their paper in 1984 described how endosonics improved canal debridement, cleansing, disinfection and shaping (Martin & Cunningham, 1984). The Cavitron unit and endosonic handpiece transfers the ultrasound to the attached file. In addition, the unit had a separate irrigation cylinder, which dispersed the antibacterial irrigant to the handpiece and along the file into the canal. This allowed simultaneous debridement, irrigation, cleaning and disinfection of the root canal. The use of a diamond coated file with the system led to efficient and rapid preparation. They concluded by stating “use of this

combination enables the dentist to perform endodontic treatment expeditiously while adhering to biologic principles”.

1.6.3 Mechanism of Action

While much of the early work focused on studying the effectiveness of the endosonic endodontic system, very little work was done in regards to the actual mechanism of action of the ultrasonic energy in the root canal system. Many of the thoughts were based on studies in other areas such as physics, water sterilization, and instrument sterilization, however, concrete evidence in endodontics was lacking. Martin had stated that the mechanism of action of ultrasound in root canal disinfection was due to the accelerated chemical activity of the antibacterial solution and the physical biologic effects (Martin, 1976). The physical biologic effects were due mainly to cavitation which is the formation of submicroscopic voids, due to shearing of the fluid medium by the alternating pressure sound waves generated by the ultrasonic instrument tip. As successive waves pass along, the acoustical shearing effect develops an enlarged bubble that grows until implosion occurs. The implosion effect creates a void that is filled with the surrounding solution under extreme hydrodynamic pressure, which causes radiating shock waves. These shock waves can rupture a cell wall or create a most effective scrubbing and cleaning mechanism due to the irregular agitation. Ahmad setup up an elaborate experimental design to examine the validity of the claims that cavitation was the key mechanism involved in ultrasonic cleaning of root canals (Ahmad & Ford, 1987). A photometric detection system was setup to record the emission of light that occurs when cavitation bubbles collapse violently. The findings suggested that cavitation did not play a role in root canal debridement with the ultrasonic system. Walmsley also evaluated

the biophysical actions of ultrasound in root canal treatment and their possible roles (Walmsley, 1987). He explained that it is theoretically possible that cavitation activity may be induced by ultrasonic instrument in the root canal, however, the development of sufficiently high sound pressure fields around the oscillating file is unlikely to occur. Lumley investigated the generation of cavitation activity during ultrasonic instrumentation and the results showed that cavitation activity could be detected with the endosonic instrument, but did not occur along the length of the file (Lumley et al, 1988). He concluded that cavitation probably only provides minor benefit in ultrasonic root canal preparation. Roy also quantified the presence of cavitation during ultrasonic instrumentation with files and observed that transient cavitation activity generally occurred near the tip of the file, provided that the wall contact did not inhibit the motion (Roy et al, 1994). In cases where there was excessive contact with the root canal walls, no cavitation was observed. However, he added that the hydrodynamic response of an oscillating file in a root canal system is extremely complex and multiple phenomena most likely contribute to the cleaning effects in a root canal. In a recent review paper, cavitation and its possible role was discussed however there still remains uncertainty as to the level at which it may contribute to ultrasonic cleaning of the root canal system (van der Sluis et al, 2007).

Acoustic streaming is the rapid movement of particles of fluid in a vortex-like motion about a vibrating object (Ahmad & Ford, 1987). This streaming is commonly associated with a vibrating file within a root canal system and has been described as acoustic microstreaming. The ultrasound energy that is transferred to the file results in a transverse oscillation along the main axis of the file. The distance of the oscillation is proportional to the amount of energy applied to the file (Ahmad et al, 1987). When the vibrating file is immersed in liquid,

these streaming patterns are formed close to the file. This streaming pattern is not random but corresponds to the characteristic pattern of nodes and antinodes along the length of the oscillating file (Walmsley, 1987). The nodes refer to the area of the file where the oscillation is minimal, while the greatest oscillation occurs at the antinodes.

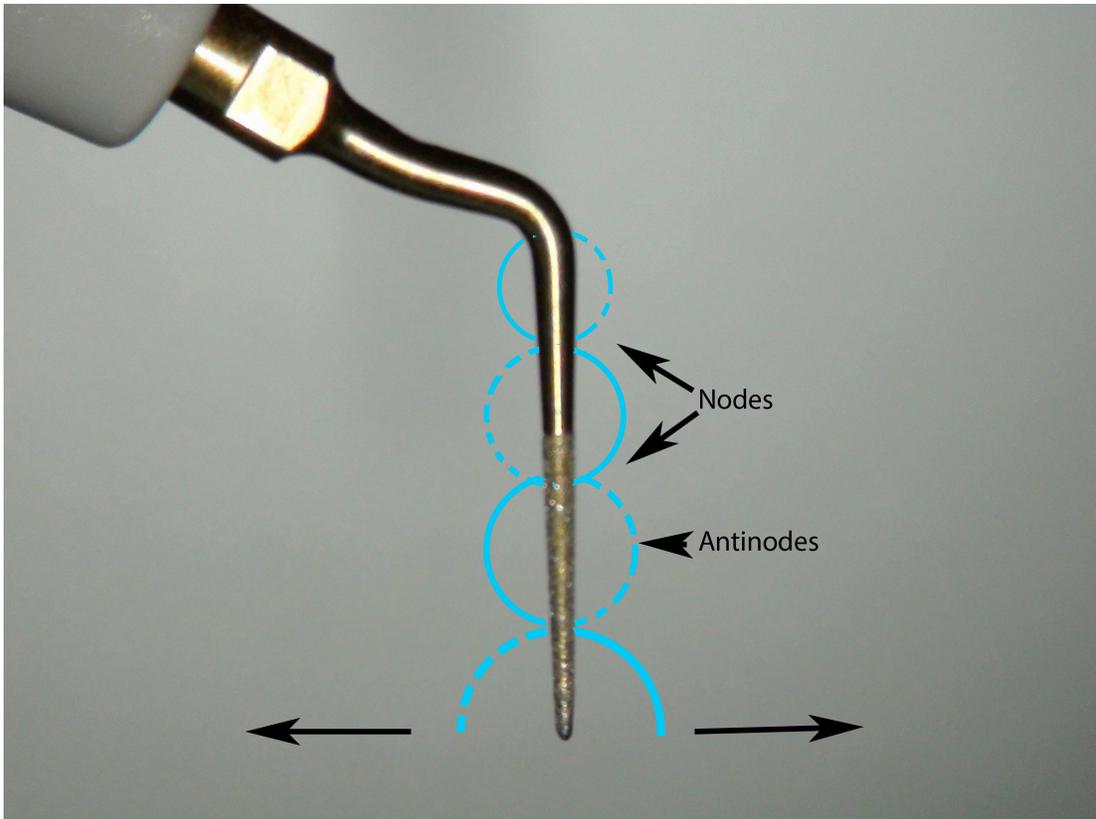


Figure 1. Ultrasonically activated tip. Diagrammatic representation showing the transverse oscillations with the antinodes (A) and nodes (N)

Acoustic streaming generates fluid motion within root canal, which creates large shear stresses on the radicular walls of the root canal. Therefore, the resulting hydrodynamic shear stresses are the dominant physical mechanism by which the surface of the root canal walls are cleaned when ultrasonic activated irrigation is applied (van der Sluis et al, 2007). The

streaming velocity can measure the movement of the liquid, which is a function of the acoustic microstreaming. The streaming velocity can be described by the equation:

$$v = \omega \varepsilon^2 / a$$

where v is the liquid streaming velocity, ω is 2π times the driving frequency, ε is the displacement amplitude of the file and a is the radius of the file. Therefore, a thinner file, higher frequency and greater displacement amplitude of the file will result in an increase in the streaming velocity (van der Sluis et al, 2007).

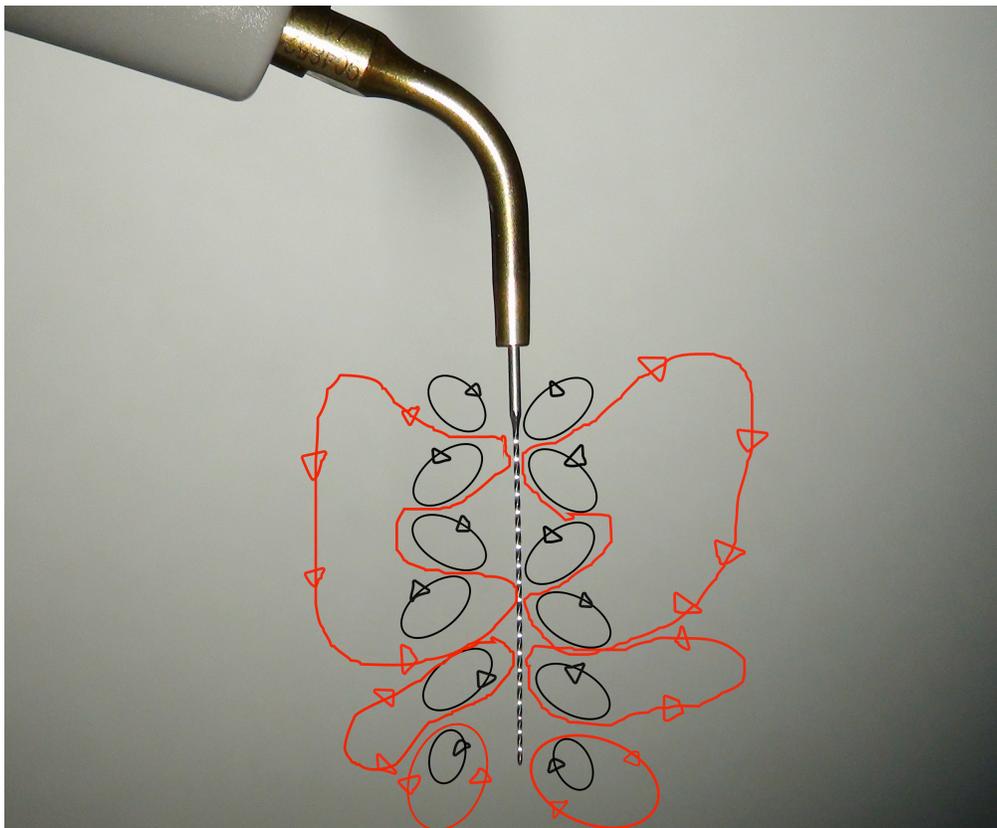


Figure 2. Acoustic streaming pattern created around a file in liquid

Ahmad's study in 1987 examined the mechanisms that may be involved with ultrasonic debridement of root canals using the endosonic files (Ahmad & Ford, 1987). The file was

activated in a plastic container filled with methylene blue solution. Polystyrene spheres that were 15 microns in diameter were placed as a thin film on the liquid surface. The file was oscillated at various settings in the solution and the spheres illuminated so that they appeared as bright white particles on a dark background. The recordings revealed acoustic streaming along the file as soon as the power was engaged. Also, fluid movement from the apical end to the coronal end of the file was observed, and this occurred in close proximity to the file surface. Additionally, an irregular array of eddying motions were observed close to the file concentrated at the apical half of the file, with the most rapid eddying occurring at the tip of the file. This study also determined that little difference in debridement existed between root canals prepared by hand and ultrasonically, with one possible reason being the dampening of the ultrasonically activated file by contact with the canal wall. In a subsequent study, Ahmad showed that smaller files (size #15), which had greater transverse displacement, generated relatively greater acoustic streaming and the streaming velocity was increased with increasing power (Ahmad et al, 1987). In addition, a modified root canal technique was employed to debride the root canals. Upon completion of instrumentation, a #15 endosonic file was inserted into the canal to full working length and allowed to oscillate for 5 minutes with a free flow of 1% sodium hypochlorite. This technique produced the cleanest canals. Walmsley's review also described how acoustic streaming is effective during ultrasonic use as it creates continuous movement of the irrigant around the canal which may potentially disrupt bacteria and debris (Walmsley, 1987). He agreed with Ahmad that the effectiveness will depend on the oscillation of the file within the root canal and this will be attenuated as contact with the walls occurs. Lumley also described the acoustic streaming pattern observed

around oscillating files by visually showed the disturbance created in plaster (Lumley et al, 1991). He concluded the ultrasonic systems produce distinctive streaming patterns with the streaming occurring in front and back of the file and the largest effect at the tip. The streaming fields are also a function of the power output and amount of restraint applied to the file. Ahmad setup another set of experiments to observe the effects of an ultrasonic file in a free field and a small channel (simulating a root canal) with different parameters (Ahmad et al, 1992). The results showed that in both groups acoustic streaming was observed with the streaming velocity higher with increasing displacement amplitude and decreasing file size. The size of the vortices was smaller in the small channels while light physical contact with the walls dampened the streaming and severe contact completely inhibited the streaming. The study concluded that it is possible to generate acoustic streaming in a confined space such as a root canal, as long as severe wall contact is avoided. It was also recommended that at some stage of the treatment that the file is allowed to vibrate freely to generate streaming in the root canal. It is recognized that the mechanisms in play are complex and many factors determine the pattern, intensity, and velocity of streaming that occurs within the root canal system.

1.6.4 Passive Ultrasonic Irrigation

Numerous studies followed the work of Martin and Cunningham to further test the validity of the endosonic technique and the reports of its superior cleaning by a combination of simultaneous ultrasonic irrigation and instrumentation. However, much of the literature supported the stance that ultrasonic instrumentation was no more effective than conventional hand instrumentation as a primary cleaning and shaping technique (Cymerman et al, 1983;

Goodman et al, 1985; Ahmad & Ford, 1987; Archer et al, 1992). In fact, it was reported that this technique had several shortcomings. It was difficult to control the shape of the prepared root canal as apical perforations and irregular shapes were produced (Stock, 1991; van der Sluis et al, 2007). As well, the ultrasonic debridement becomes inefficient due to constraint within the root canal, especially in curved canals (Walmsley & Williams, 1989). A critical study was done by Weller who compared the efficacy various techniques for debridement of the root canal system (Weller et al, 1980). Using extracted teeth and resin blocks filled with radioactive gelatin, instrumentation was performed with hand filing alone, ultrasonic instrumentation, or hand filing followed by ultrasonic cleaning. The results showed that there was no difference between hand instrumentation and ultrasonic instrumentation alone as both techniques reduced radioactivity by 79% and 77% respectively. However, the combination of the hand instrumentation followed by the ultrasonic was the most efficient method and reduced the radioactivity by 88%. Weller recommended that ultrasonic activation should be used as an adjunct to conventional hand instrumentation to improve the efficiency of debridement, and not be used as an alternative. This technique became known as passive ultrasonic irrigation (PUI) since the activated ultrasonic file is not used to instrument or actively cut the root canal walls (van der Sluis et al, 2007). After the root canal has been instrumented to the master apical size, irrigant is placed into the canal. An ultrasonic handpiece with a #15 file is introduced into the root canal and placed to the working length. The ultrasonic unit is energized and the oscillating file will transfer energy to activate the irrigant. This results in the formation of acoustic of the irrigant, which can improve the removal of debris, bacteria, and tissue within the root canal system, particularly

the apical region (Krell et al, 1988). Since there is no cutting of the canal walls with the file, the potential to create iatrogenic errors within the tooth is reduced.

1.6.4.1 Flushing Methods with Passive Ultrasonic Irrigation

The literature shows that there are two flushing methods that can be used during PUI, a continuous flush of irrigant from the ultrasonic handpiece or an intermittent flush technique by using syringe delivery (Gu et al, 2009). Most of the literature has evaluated PUI with the intermittent flush technique. The efficacy of the continuous flow method will be discussed later. In the intermittent flushing method, the irrigant is delivered into the root canal by a syringe needle and then activated by an oscillating ultrasonic file. The root canal is then flushed with fresh irrigant to remove the loose debris and tissue remnants from the canal walls. This cycle can be repeated several times to optimize the cleaning. van der Sluis compared the flushing methods during PUI to remove artificially replaced debris from the apical portion of the root (van der Sluis et al, 2010). He concluded that there was no difference between intermittent and continuous flushing. Zeltner evaluated temperature changes associated with PUI in extracted teeth (Zeltner et al, 2009). The experimental design recorded the temperature changes during PUI with continuous flow and intermittent flushing. The intermittent method showed raised irrigation solution temperatures during the PUI while the continuous flow seemed to negate any increases in temperature of the irrigant. Increasing the temperature has been associated with increased effectiveness of sodium hypochlorite, however the effects of increased temperature to the surrounding tissues is unknown (Cameron, 1988)

1.6.4.2 The Effectiveness of Passive Ultrasonic Irrigation

Goodman compared the effectiveness of hand instrumentation against a preparation that used hand instrumentation followed by ultrasonic energy on the tissue removal from the mesial root canals of 60 extracted human mandibular molars (Goodman et al, 1985). A size 15 K-type file was attached to the ultrasonic unit and activated for 3 minutes per canal after completion of hand instrumentation. Histological analysis was employed to measure the tissue removal in the canal and isthmuses at the 1 mm and 3 mm level. The results showed that the hand instrumentation followed by ultrasonic activation produced significantly cleaner isthmuses at both levels and canals at the 1 mm level, compared to the hand instrumentation alone. Archer also compared the debridement efficacy of the hand instrumentation against hand preparation with ultrasonics in an in vivo studying using mandibular molars (Archer et al, 1992). Following extraction and histological preparation, 0.2-micron cross-sections from the 1- to 3-mm apical levels of the canal and isthmus were evaluated for percentage of tissue removal. Canal and isthmus cleanliness was significantly higher at all levels with the ultrasonic irrigation technique. Jensen compared the cleaning efficacy of passive ultrasonic irrigation in curved roots of extracted molar teeth using photomicrographs (Jensen et al, 1999). The canals were shaped to an apical size of 35 and PUI was applied for 2 minutes, using a size #15 file attached to the ultrasonic unit. The remaining debris was significantly lower for the PUI groups compared to hand filing alone. Sabins evaluated the effectiveness of sonic and ultrasonic passive irrigation in maxillary molars, after hand instrumentation, to reduce debris when used for as little as 30 or 60 seconds (Sabins et al, 2003). He concluded that PUI, for as little as 30 seconds after hand instrumentation, produced canals with significantly less debris than canals instrumented by hand instrumentation and without PUI.

Spoleti evaluated the effectiveness of PUI in a bacteriologic study using extracted canines and sterile saline as the irrigant (Spoleti & Siragusa, 2003). The results showed that PUI led to less surviving bacteria in the root canals. He concluded that ultrasound seems to improve the disinfection of infected root canals probably because organic tissues entering the streaming field generated by ultrasonic activation are disrupted. To assess debris removal, Lee created a split tooth model using extracted canines with artificially made grooves and depressions at 2, 4, and 6 mm from the apex (Lee & Wu, 2004). With this model, the effectiveness of dentin debris removal with PUI and syringe irrigation was compared. After application of the irrigation protocols, microscopic images were recorded and the debris removal in the teeth was graded. The results indicated that ultrasonic irrigation was capable of removing more artificially placed dentine debris from simulated canal irregularities in straight, wide root canals than syringe irrigation. Rodig looked at the cleaning efficacy of different irrigant agitation techniques on debris and smear layer removal in curved root canals (Rödig et al, 2010). Scanning electron microscopy was used to analyze the samples and the results revealed no significant differences in debris removal at any level regardless of the technique used, including ultrasonics. There was a significant improvement in smear layer removal with the agitation techniques, but only at the straight coronal portion of the canal.

A recent study compared the effectiveness of ultrasonic activated irrigation on debris removal in curved and straight canals (Amato et al, 2011). Amato examined 6 straight and 6 curved roots with a split model design. Artificially created grooves were placed in the dentin walls at 2, 4, and 6 mm from the apex. These grooves were filled with dentin debris and the effectiveness of a 30 gauge syringe needle, PUI and a hydrodynamic device was evaluated.

The results showed that the PUI was significantly more effective for debris removal in the straight canals compared to syringe irrigation, however, the hydrodynamic device was significantly more effective in the curved canals. There was no significant difference between PUI and syringe irrigation in the curved canals and this may be attributed to contact with the canal walls, which may dampen the ultrasonic effect. Overall, the literature supports the claim that PUI is more effective than conventional syringe irrigation in removing tissue, bacteria, and debris, however, PUI is unable to completely debride the root canal system.

1.6.4.3 Factors Influencing Passive Ultrasonic Irrigation

Moorer identified ultrasonic agitation as one of the factors that improved the tissue dissolution effect of sodium hypochlorite in his study (Moorer & Wesselink, 1982). Cameron also concluded in his study that there is a synergistic relationship between sodium hypochlorite and ultrasound when used in combination in regards to debris and smear removal from instrumented root canals (Cameron, 1987). More recently, Stojicic demonstrated the increased tissue dissolution effect of sodium hypochlorite with ultrasonic activation (Stojicic et al., 2010). Therefore, the combined use of sodium hypochlorite and ultrasound appears to be advantageous in root canal disinfection.

van der Sluis demonstrated that there is no difference in regards to debris removal from artificial grooves between a 15 K file and a smooth wire, when used for ultrasonic irrigation (van der Sluis et al, 2005a). This may be advantageous as there would be no risk of damage to the canal wall by the cutting action of a K file.

van der Sluis also examined the effect of ultrasonic irrigation on canals prepared with varying tapers (van der Sluis et al, 2005b). He concluded that ultrasonic irrigation was more effective in removing artificially placed dentine debris from simulated canal extensions from canals with greater tapers.

Jiang evaluated the effect of ultrasonic intensity on the cleaning efficacy of PUI inside a root canal (Jiang et al, 2011). The ability to remove dentinal debris root canals with varying ultrasonic power settings was assessed. The study concluded that higher ultrasonic intensity resulted in higher amplitude of the oscillating file and consequently an increased velocity of the irrigant around the file. Higher ultrasonic power settings led to increased efficacy of cleaning by PUI.

The direction of movement of the oscillating file during PUI, in relation to the location of debris and shape of the canal, can influence the effectiveness debris removal in a root canal. Lumley showed that with large oval shaped canals the ultrasonically activated file oscillated should be directed towards the recesses of the canal to maximize the debris removal and streaming of the irrigant (Lumley et al, 1993). Jiang also investigated this feature and concluded that the oscillation of the ultrasonically driven file is more effective in debris removal if it towards the groove compared to perpendicular to the groove (Jiang et al, 2010). There appears to be a higher velocity of irrigant generated from the file tip in a single direction, typically in front of and behind the file and parallel to the handpiece. Therefore, it is important to maximize the ultrasound energy by orienting the ultrasonic tip in the correct orientation.

1.6.5 Continuous Flow Ultrasonic Irrigation

Continuous flow ultrasonic irrigation is the use of a continued supply of irrigant that is delivered from the ultrasonic handpiece into the root canal system during ultrasonic activation. This type of irrigation delivery system offers several potential advantages. The delivery of fresh irrigant into the root canal is highly desirable since sodium hypochlorite is unstable and rapidly consumed when introduced into the root canal system (Moorer & Wesselink, 1982). The organic contents of the root canal system consume the available chlorine and reduce its antibacterial activity, therefore it is important to frequently exchange and replenish the irrigant to maintain its antibacterial and tissue dissolving effectiveness (Siqueira et al., 2000). A continuous flow device has the ability to deliver an increased volume of irrigant and this can also be beneficial in the disinfection of the root canal system (Sedgley et al, 2004). The continuous flow of irrigant can also act to dissipate any heat that is produced by the ultrasonic irrigation type and prevent excessive heating within the root canal system (Cameron, 1988).

A group from Ohio State University developed an ultrasonically activated irrigating needle as an adjunctive device for root canal debridement and disinfection. During ultrasonic activation, a 25 gauge irrigation needle is used instead of an endosonic file and this allows simultaneous ultrasonic activation with irrigant delivery from a syringe. This device allows irrigant to be delivered apically through needle under a continuous flow of irrigant during the ultrasonic activation.



Figure 3. Continuous flow ultrasonic irrigation prototype setup (Courtesy Dr. John Nusstein)

This device was used in an in vivo, randomized, prospective, single-blinded study to histologically compare debridement efficiency of a hand/rotary instrumentation against a hand/rotary instrumentation with continuous flow ultrasonic irrigation in the mesial roots of vital human mandibular molars (Gutarts et al, 2005). 36 adult volunteers participated in this study and 15 teeth were prepared using the hand/rotary instrumentation followed by 1 minute of ultrasonic irrigation per canal at a flow rate of 15 ml/min. Histologic sections were taken from the 1 to 3 mm levels and analyzed for debris cleanliness in the canal and isthmus. The study concluded that the 1 minute use of the continuous flow ultrasonic irrigation after instrumentation resulted in significantly cleaner canals and isthmuses in the mesial roots of mandibular molars. The authors reported that the continual deposition and renewal of irrigating solution in the canal might have contributed to the improved cleanliness of the canal. In addition, the larger size needle allows the ultrasonic unit to be used at a higher energy, which may have contributed to the cleaner canals and isthmuses.

In a subsequent study by Burleson, the same system was used to assess the debridement efficacy of necrotic debris and biofilms in the mesial roots of human, necrotic, mandibular molars (Burleson et al, 2007). Once again, statistical analysis revealed the canal and isthmus cleanliness values to be significantly higher for the continuous flow ultrasonic irrigation technique at all levels evaluated. The study concluded that 1 minute of ultrasonic activated irrigation has been shown to improve canal and isthmus cleanliness in regards to necrotic debris and biofilm removal.

The third study by the Ohio State group evaluated the in vivo antibacterial efficacy of continuous flow ultrasonic irrigation after hand and rotary instrumentation in human, necrotic mandibular molars (Carver et al, 2007). Treatment groups were divided into 16 mesial roots prepared by hand/rotary instrumentation, and 15 mesial roots prepared similarly, but followed by 1 minute of continuous flow ultrasonic irrigation per canal at a flow rate of 15 ml/min. Each canal was sampled before and after hand/rotary instrumentation and after ultrasonic irrigation. Samples were incubated in an anaerobic chamber, and colony forming units were counted. The addition of 1 minute of ultrasonic irrigation resulted in significant reduction of positive cultures. Logistic regression analysis indicated the addition of ultrasonic irrigation was 7 times more likely to yield a negative culture (Carver et al, 2007). The ultrasonically activated needle tested in these studies was the prototype for the commercially available ProUltra PiezoFlow (Dentsply Tulsa Dental Specialties, Tulsa, OK).

Adcock utilized a closed-canal system to compare the canal and isthmus debridement efficacies of a 30 gauge side-venting needle and a continuous flow ultrasonic irrigation system (Adcock et al, 2011). Micro-computed tomography scanning was used to select 20 mandibular molars that contained a narrow isthmus in the mesial root. The canals were

instrumented to size 40, 0.04 taper and assigned to two groups. The first group was irrigated with 15 ml of 6% sodium hypochlorite followed by 15 ml of 17 % EDTA using the 30 gauge side-venting needle. The second group was irrigated with the same irrigants but delivered using the ProUltra PiezoFlow Ultrasonic irrigation system (Dentsply Tulsa Dental Specialties). The study concluded that there was no difference in the canal debridement efficacy between the 2 groups at any level in the apical third. However, the continuous flow irrigation produced significantly cleaner isthmuses than the 30 gauge side-venting needle from 1.0 to 2.2 mm from the apex. In addition, neither technique was capable of completely debriding the canal of isthmus of the mesial roots.

Harrison investigated the ability of a continuous flow ultrasonic irrigation system to eliminate *E. faecalis* from the canal wall and dentinal tubules of extracted teeth (Harrison et al, 2010). Straight teeth were instrumented and subjected to the ultrasonic activation for 1 minute with 1% sodium hypochlorite at a flow rate of 5 ml/min, followed by a one week application of calcium hydroxide. The study concluded that the ultrasonic irrigation may be effective in enhancing microbial control of infected root canals, however, complete eradication of bacteria from within the dentinal tubules was not achieved, despite the use of calcium hydroxide as an intracanal medication.

In a very recent study, Jiang evaluated the removal of dentin debris from artificially made grooves in straight root canals by 6 different final irrigation techniques, one of which was a continuous flow ultrasonic irrigation device (Jiang et al, 2012). The VPro StreamClean (Vista Dental, Racine, WI) is an ultrasonically activated, 30-gauge irrigation needle that was used for the continuous flow ultrasonic irrigation in this study. Jiang concluded that

continuous flow ultrasonic irrigation was the most effective technique in dentin debris removal from the apical irregularities, and syringe irrigation alone was the least effective.

Altogether, numerous studies have shown the increased disinfection with the utilization of ultrasonic irrigation in root canal treatment. Based on the limited research, the addition of the continuous flow ultrasonic irrigation devices appears to be promising, however further studies are required to better quantify their results and fully understand the mechanisms involved.

1.7 Objectives

The aims of this study are to:

1. To compare the efficacy of continuous flow ultrasonic irrigation systems to conventional syringe irrigation in removing debris and smear layer from straight and curved root canals.
2. Understand the mechanisms by which these devices function.
3. Understand the benefits and shortcomings of these devices.
4. Assess the possible clinical implications in the application of these devices.

1.8 Hypothesis

The use of continuous flow ultrasonic irrigation devices will be more effective in the cleaning of root canal walls than conventional irrigation delivery with a syringe and side-vented needle alone.

Chapter 2: Material and Methods

2.1 Experimental Design

This in vitro study was designed to compare two continuous flow ultrasonic irrigation systems to conventional syringe/needle irrigation in the apical portion of straight and curved root canals. Two parameters were measured and analyzed: (1) the amount of debris remaining on the root canal walls, as expressed by the percentage of debris remaining, and (2) the amount of smear layer remaining, which was measured using a scoring system.

2.2 Tooth Selection and Preparation

This study was conducted using recently extracted human mandibular molars and maxillary anterior teeth that had mature apices, no caries, intact crowns, and no previous endodontic treatment. After extraction, the teeth were placed in a 0.01 % NaOCl solution and stored at 4 ° C. Twenty-four maxillary anterior teeth (maxillary central, lateral, and canines) and 21 mandibular molars were selected. The root canal curvatures were measured by Schneider's method (Schneider, 1971) and ranged from 15 to 30 degrees for the mesial roots of the mandibular molars (curved roots). The anterior teeth were all less than 10 degrees in curvature (straight roots). A standard access cavity preparation was made in the teeth and the working length was determined by inserting a size 10 stainless steel K file (Dentsply Maillefer, Tulsa, OK) into the canals until the tip of the instrument was just visible at the apical foramen. Creating a closed system in the teeth simulated the clinical situation. The apical portions of the roots were coated with laboratory wax and this coating sealed the apical foramen and accessory canals. The canals were shaped using ProTaper Sx-S1-S2 and Profile Vortex rotary nickel-titanium instruments (Dentsply Tulsa Dental Specialties) using a

crown-down technique. After each instrument change, manual irrigation was performed with 1 mL NaOCl, using a syringe and 30 gauge side-venting needle (Prorinse: Dentsply Tulsa Dental Specialties). The needle was inserted as deep apically as possible without binding. The straight anterior teeth were shaped to size 40.04 and the curved mesial roots were shaped to size 35.04. A nickel titanium hand file (Dentsply Tulsa Dental Specialties) was used to gauge and confirm the final apical size of all teeth. The final shaping was aimed to create a clinical relevant shape and final apical size. The same operator performed all the procedures.

2.3 Experimental Groups

The maxillary anterior teeth and mesial roots of the mandibular molar teeth were randomly assigned to the experimental groups according to the final irrigation technique. Each group received the same post-instrumentation final irrigation volume of 15 mL of 3% NaOCl.

Straight canals-taken from the maxillary anterior teeth

- Group 1: (n=8): Conventional syringe irrigation. The teeth were irrigated with positive pressure using a 30 gauge Prorinse needle (Dentsply Tulsa Dental Specialties) and syringe. The needle was placed 1 mm short of the working length for the delivery of 15 mL of 3% NaOCl.
- Group 2 (n=8): VPro StreamClean System (Vista Dental). Continuous flow ultrasonic irrigation was performed using the VPro StreamClean system (Vista Dental) at a power setting of 4 using a ProUltra Piezo Ultrasonic Booster (Dentsply Tulsa Dental Specialties). This ultrasonic tip is a 30-gauge needle, enabling a continuous flow of irrigant from the tip with a simultaneous ultrasonic oscillation of the tip. The needle

was introduced into the canal, taken 1 mm short of the working length and activated. This procedure resulted in a total irrigant volume of 15 mL, which was delivered to the needle by the Vatea Endodontic Irrigation System (ReDent Nova Ltd., Ra'anana, Israel) at a flow rate of 15 mL/min. The total irrigation delivery and activation time was 1 minute.

- Group 3 (n=8): ProUltra PiezoFlow Ultrasonic Irrigation Needle (Dentsply Tulsa Dental Specialties). This system uses a rigid 25 gauge needle that is equipped with an attachment for an irrigation source. The needle is attached to an ultrasonic handpiece to facilitate continuous flow ultrasonic irrigation. The needle is inserted into the canal to determine the length at which the needle binds against the canal walls. The manufacturer recommends to pull the needle back 1 mm from the binding point and record the depth, however, the needle depth should not be taken greater than 75% of the working length and should not be taken to the apex of the canal. The ultrasonic unit was set at power level 5 and irrigation flow rate was 15 mL/min. The Vatea Endodontic Irrigation System (ReDent Nova Ltd.) was also used to deliver the irrigant continuously. The needle was activated for 1 minute in each canal and a total volume of 15 mL was delivered.

Curved canals-taken from the mesial roots of mandibular molars:

- Group 4 (n=7): Same as group 1
- Group 5 (n=7): Same as group 2
- Group 6 (n=7): Same as group 3

In all groups, 3 mL of 17% EDTA was delivered into each canal for 2 minutes for smear layer removal using a syringe and a 30-gauge Prorinse needle, which was placed 1 mm from working length. This was followed by 3 mL of sterile water to neutralize the effects of the 17% EDTA.



Figure 4. Ultrasonic experimental setup. Ultrasonic unit with handpiece, irrigation delivery unit, and VPro StreamClean Ultrasonic Needle.

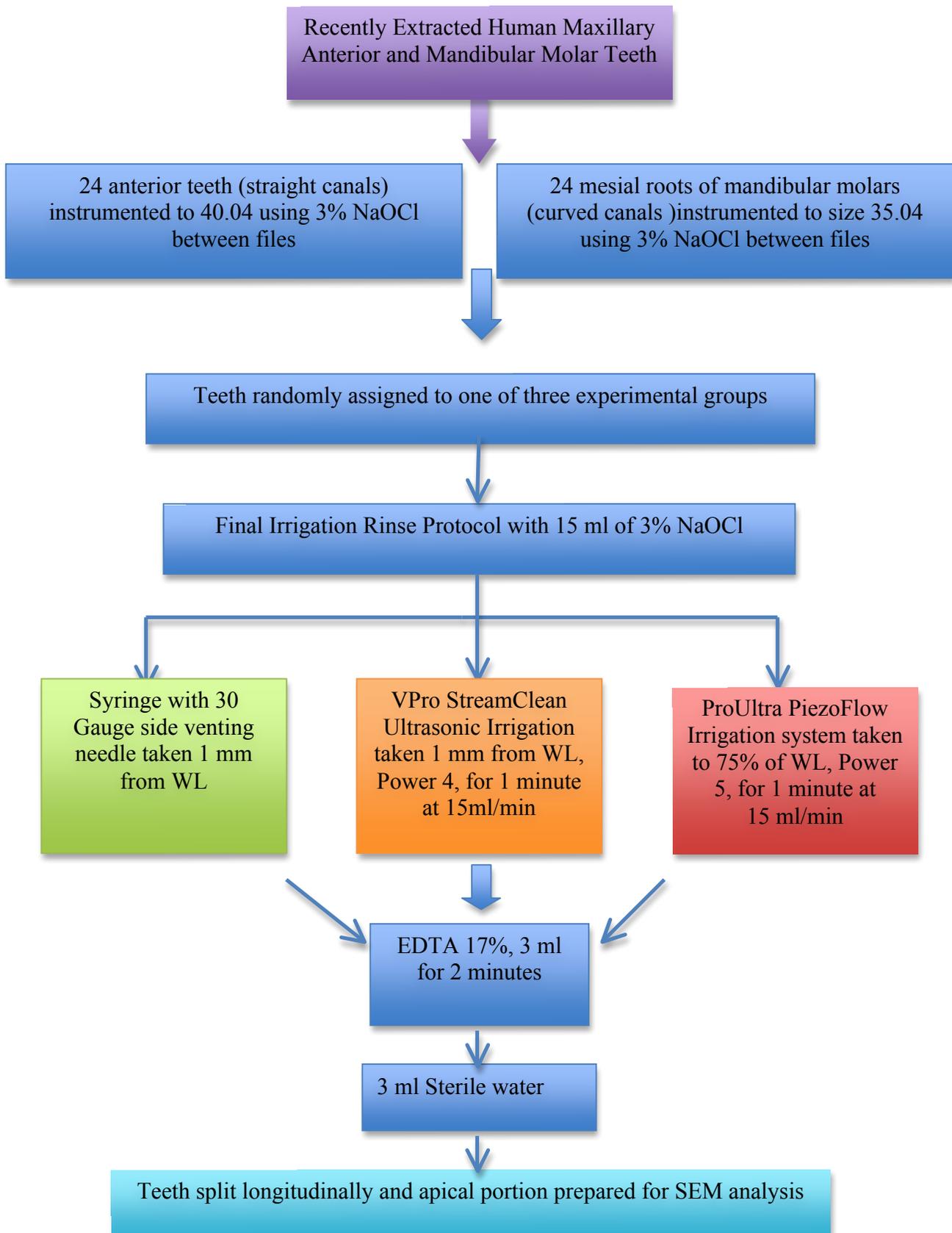


Figure 5. Irrigation needles used in experimental groups. (From top) ProUltra PiezoFlow needle, VPro StreamClean needle, ProRinse side-venting needle

2.4 Sectioning of Teeth and Preparation for SEM

After irrigation, the roots of the anterior teeth and mesial roots of the mandibular molars were removed from the crowns using a diamond coated disc. The orifices were covered with laboratory wax to prevent dentine debris from entering the canal. The roots were marked at 1, 3 and 5 mm from the canal terminus on both the mesial and distal sides. The root surface was notched using the diamond coated disc and then were split longitudinally in a buccolingual direction using a sterile razor blade. The samples were then dehydrated by successive soaking cycles using 50%, 70%, 80% and 100% ethanol. Following this, the samples were subjected to critical point drying and stored in a 58 ° C oven. The dried samples were mounted on aluminum stubs and coated with gold-palladium in a Hummer VI sputter (Technics West Inc., San Jose, CA).

Figure 6. Experiment Flowchart



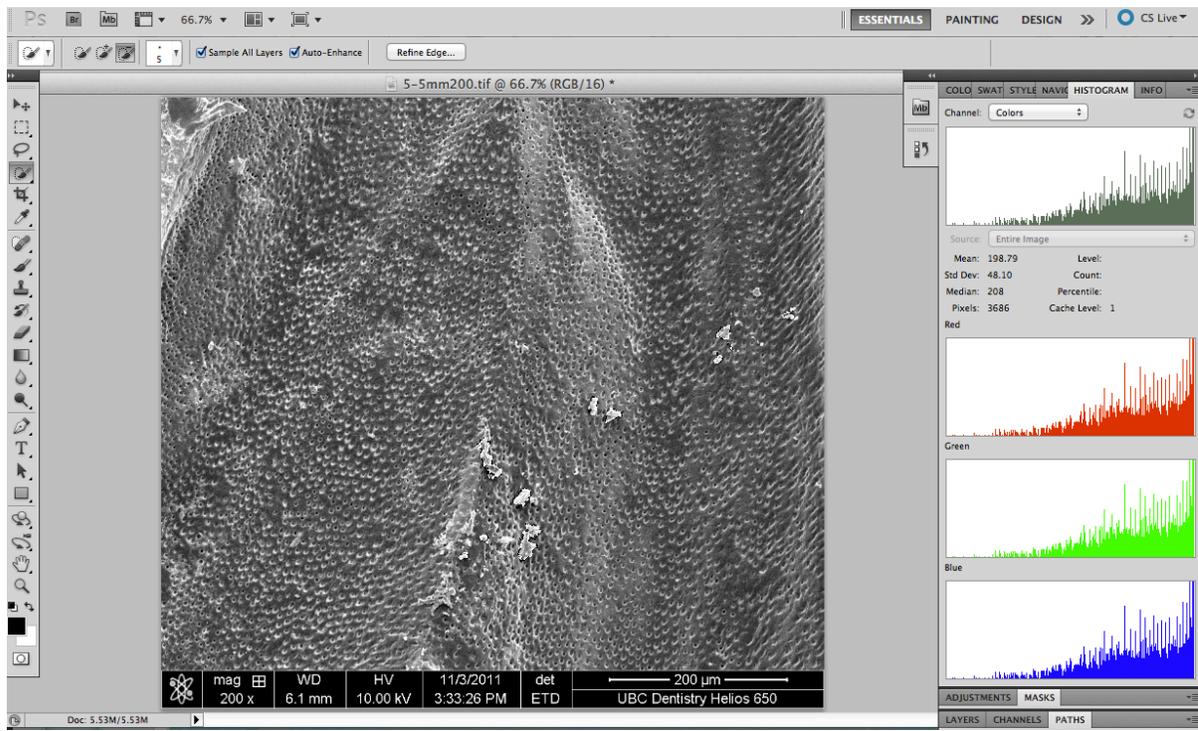
2.5 SEM Evaluation

Each sample was first viewed at a low magnification (20x) to gain an overview of the sample using the scanning electron microscope (Stereoscan 260, Cambridge Instruments, Cambridge, UK and Helios Nanolab 650, FEI, Oregon, USA). Images were recorded at 1, 3 and 5 mm from the canal terminus, using the markings that were made on the roots before sectioning as a reference. Image acquisition was blinded for all samples.

2.5.1 Debris Evaluation

Debris was defined as dentin chips, pulp remnants, and particles loosely attached to the root canal surface (American Association of Endodontists, 2003). Image acquisition for debris evaluation was performed at 200x magnification with images taken at 1, 3, and 5 mm from the apex. The images were uploaded into Adobe Photoshop CS5 Extended (Adobe Systems, San Jose, CA) to calculate the percentage of debris on root canal wall surface at the designated canal level. The debris in each canal was traced using the selection tool and the total number of pixels occupied by the debris was reported by using the histogram function in the software program. The total canal area visible in the image was outlined using the selection tool and the same feature of the software reported the total pixels occupied by the canal. Percentage of debris was calculated by dividing the pixels of debris by the total pixels representing the total area of the canal. Percentage of debris was calculated for 1, 3 and 5 mm from the apex. The operator was blinded for all image analysis of debris calculations.

Figure 7. Adobe Photoshop software using selection tool for debris calculation



2.5.2 Smear Layer Evaluation

Smear layer was defined as the surface film of debris retained on dentin or other surfaces after instrumentation with either rotary instruments or endodontic files; consists of dentin particles, remnants of vital or necrotic pulp tissue, bacterial components, and retained irrigant (American Association of Endodontists, 2003). Images for smear layer evaluation were taken at 1000x magnification. For each level (1, 3, or 5 mm), 5 images were captured using stratified randomized sampling. An area was randomly selected in the canal and an image captured. Subsequent images were taken 100 microns from the original area in each direction, to give a total of 5 images. The presence of smear layer was graded by two

calibrated observers using a 5 point scale as described by Caron (Caron et al, 2010). All grading was blinded. The scoring was as follows:

- Score 1: no smear layer and dentinal tubules open
- Score 2: small amounts of scattered smear layers and dentinal tubules open
- Score 3: thin smear layer and dentinal tubules partially open
- Score 4: partial covering with a thick smear layer
- Score 5: total covering with a thick smear layer

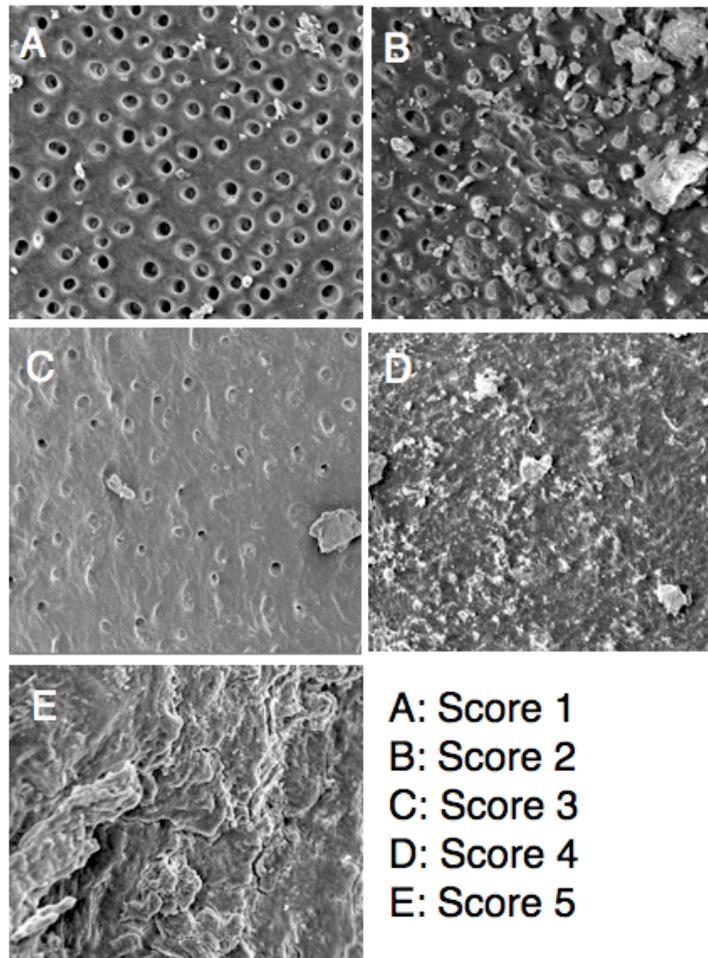


Figure 8. Smear layer grading scale

2.6 Statistical Analysis

Debris data was analyzed using a one-way analysis of variance (ANOVA) with a Dunnett's test to determine significant differences between the groups. The median value of the 5 smear layer scores was determined for each level and analyzed using the Kruskal-Wallis test with a Dunn's multiple comparison. The significance level was set at 0.05 for both sets of tests.

The interclass correlation coefficient was calculated to assess the inter-observer agreement of the smear layer scores for the two observers. In addition, the inter-examiner and intra-examiner reliability was calculated. This was determined by analyzing the grading of a set of smear layers scores by the two observers, which were done 4 weeks apart. PASW 18 Software (SPSS Inc., Chicago, IL, USA) and Prism 5 (Graphpad Software, La Jolla, CA, USA) were used for the statistical analysis.

Chapter 3: Results

3.1 Debris Removal

There was no statistically significant difference in debris removal with the continuous flow ultrasonic irrigations systems compared to conventional syringe irrigation alone at each level evaluated in both the straight and curved canals ($p>0.05$). A comparison of the debris results for all groups is shown in Table 1 and Figures 9-14. The Bartlett's test for variance revealed significant differences between the variances for all groups and at all levels ($p<0.01$). This may indicate that the groups represent different populations regardless of no differences in the means.

Table 1. Mean percentage of remaining debris with standard deviations

Level	Conventional Syringe	VPro Stream Clean	ProUltra PiezoFlow
Anterior Straight Canals (n=8)			
1 mm	37.76 ± 38.47	19.92 ± 33.55	7.60 ± 7.17
3 mm	28.23 ± 27.04	20.31 ± 27.37	5.01 ± 4.55
5 mm	14.02 ± 20.18	7.02 ± 12.43	3.49 ± 4.34
Posterior Curved Canals (n=7)			
1 mm	24.46 ± 34.66	15.95 ± 25.11	10.14 ± 4.78
3 mm	8.04 ± 14.25	10.13 ± 16.61	4.57 ± 4.17
5 mm	7.99 ± 7.19	4.57 ± 2.52	4.08 ± 2.83

Debris 1 mm from the apex-Straight canals

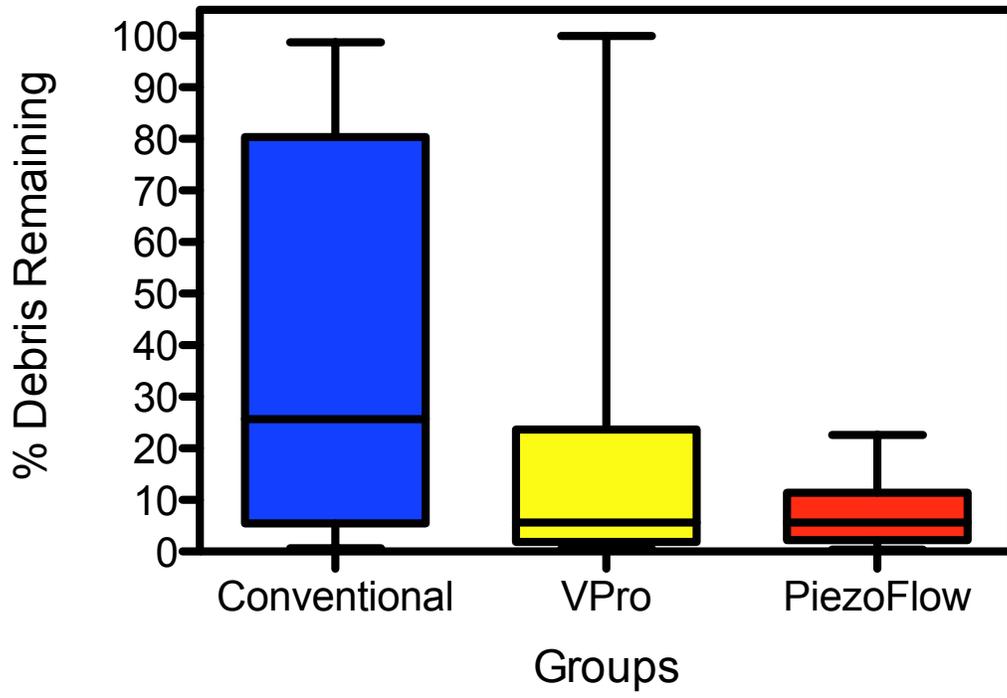


Figure 9. Comparison between groups according to debris remaining at 1 mm from the apex in straight canals. $P > 0.05$

Debris 3 mm from the apex-Straight canals

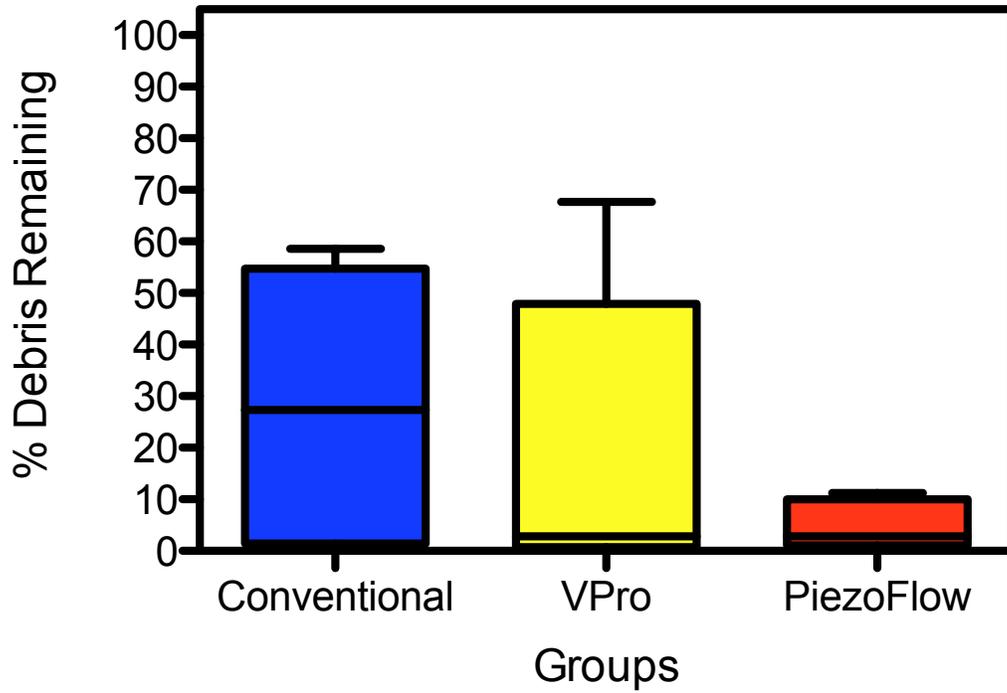


Figure 10. Comparison between groups according to debris remaining at 3 mm from the apex in straight canals. $P > 0.05$

Debris 5 mm from the apex-Straight canals

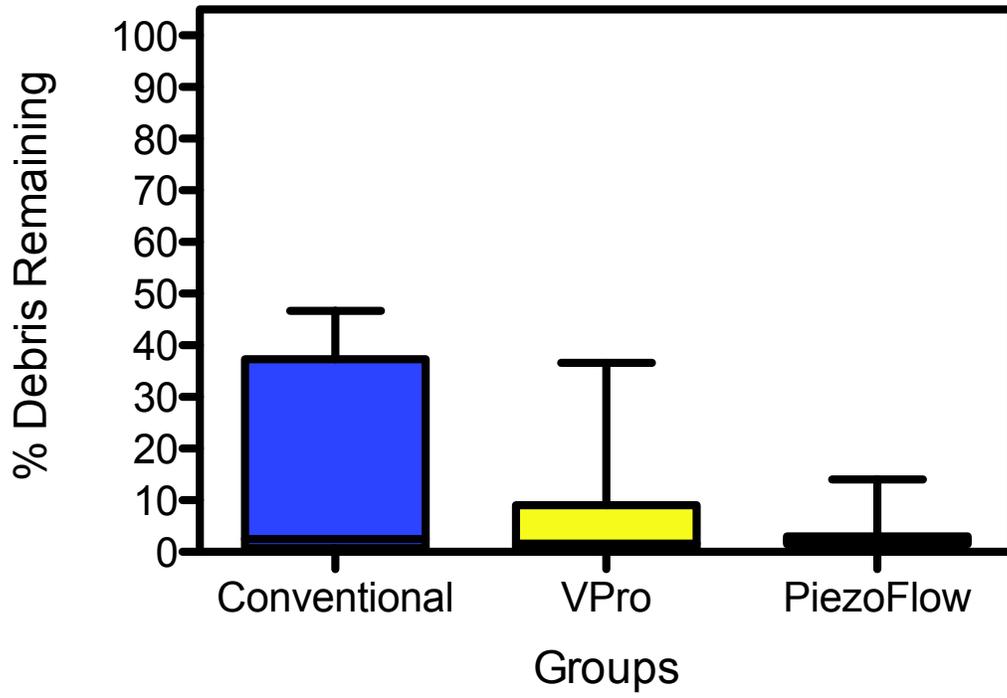


Figure 11. Comparison between groups according to debris remaining at 5 mm from the apex in straight canals. $P > 0.05$

Debris 1 mm from the apex-Curved canals

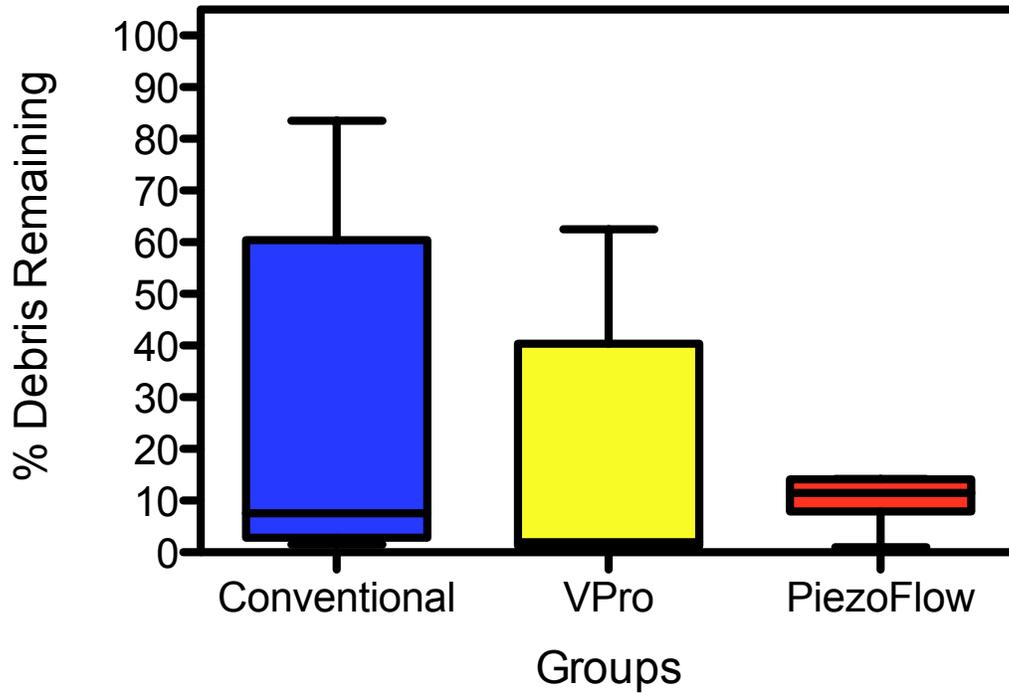


Figure 12. Comparison between groups according to debris remaining at 1 mm from the apex in the curved canals. $P > 0.05$

Debris 3 mm from the apex-Curved canals

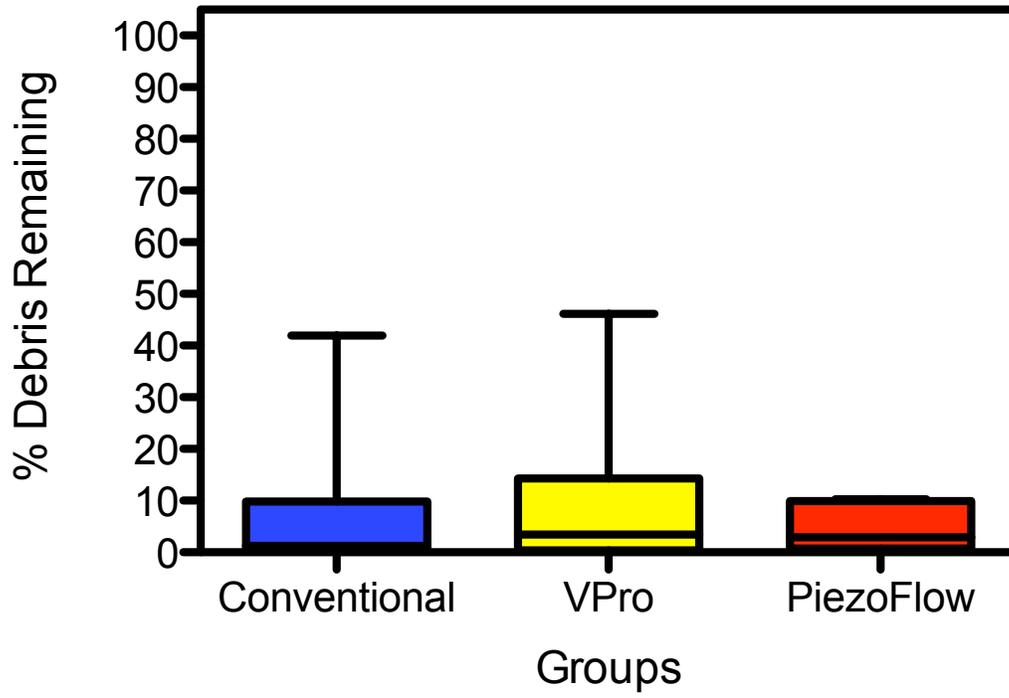


Figure 13. Comparison between groups according to debris remaining at 3 mm from the apex in the curved canals. $P > 0.05$

Debris 5 mm from the apex-Curved canals

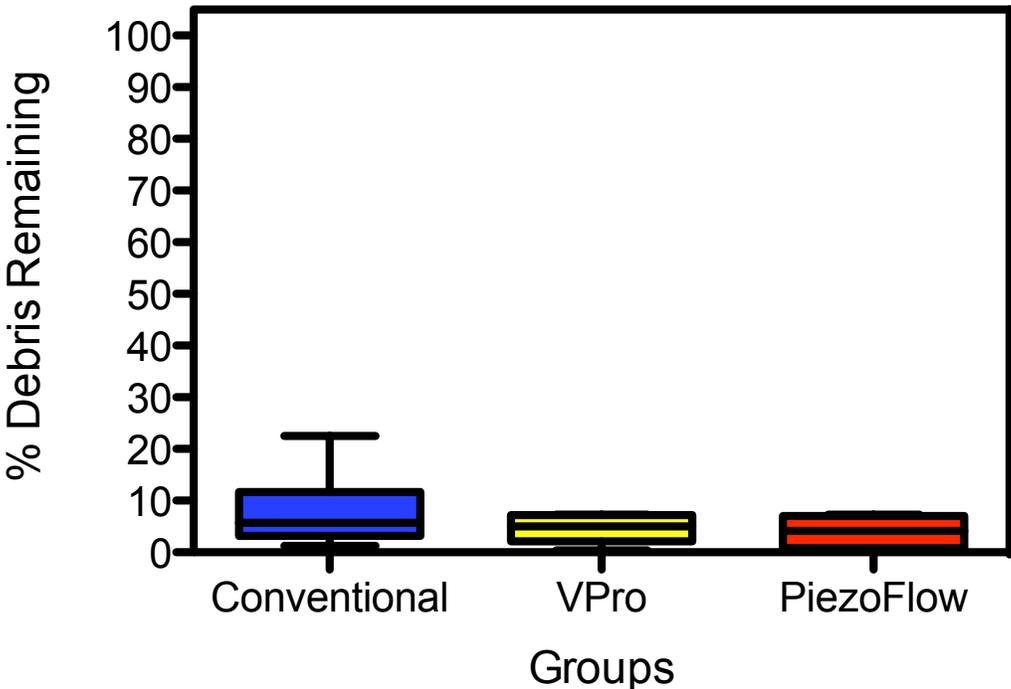


Figure 14. Comparison between groups according to debris remaining at 5 mm from the apex in the curved canals. P >0.05

3.2 Smear Layer

The interclass correlation coefficient determined to be 0.974 for the 1 mm level, 0.975 for the 3 mm level, and 0.982 for the 5 mm level. The inter-examiner reliability was 0.847 and the intra-examiner reliability was 0.855 for observer A and 0.870 for observer B.

At the 1 mm level in the straight teeth, the PiezoFlow system showed a statistically significant difference in smear layer compared to the conventional syringe irrigation ($p=0.018$). There were no significant differences at the 3 mm or 5 mm level in the straight canals. In regards to the curved canals, there were no statistically significant differences among the groups at any levels for smear layer. A comparison of the results between the groups can be seen in Figures 15-20.

Table 2. Mean smear layer scores with standard deviations for all groups and levels

Level	Conventional Syringe	VPro Stream Clean	ProUltra PiezoFlow
Anterior Straight Canals (n=8)			
1 mm	4.88 ± 0.35	4.25 ± 1.04	3.25 ± 1.28 *
3 mm	3.38 ± 1.60	3.13 ± 1.13	3.25 ± 1.28
5 mm	2.88 ± 1.46	2.00 ± 0.76	2.50 ± 0.53
Posterior Curved Canals (n=7)			
1 mm	3.63 ± 1.41	3.00 ± 1.16	3.43 ± 1.27
3 mm	2.50 ± 1.12	2.29 ± 0.49	2.43 ± 0.79
5 mm	2.13 ± 1.25	1.43 ± 0.53	1.29 ± 0.49

* $p<0.05$

Smear 1 mm from the apex-Straight canals

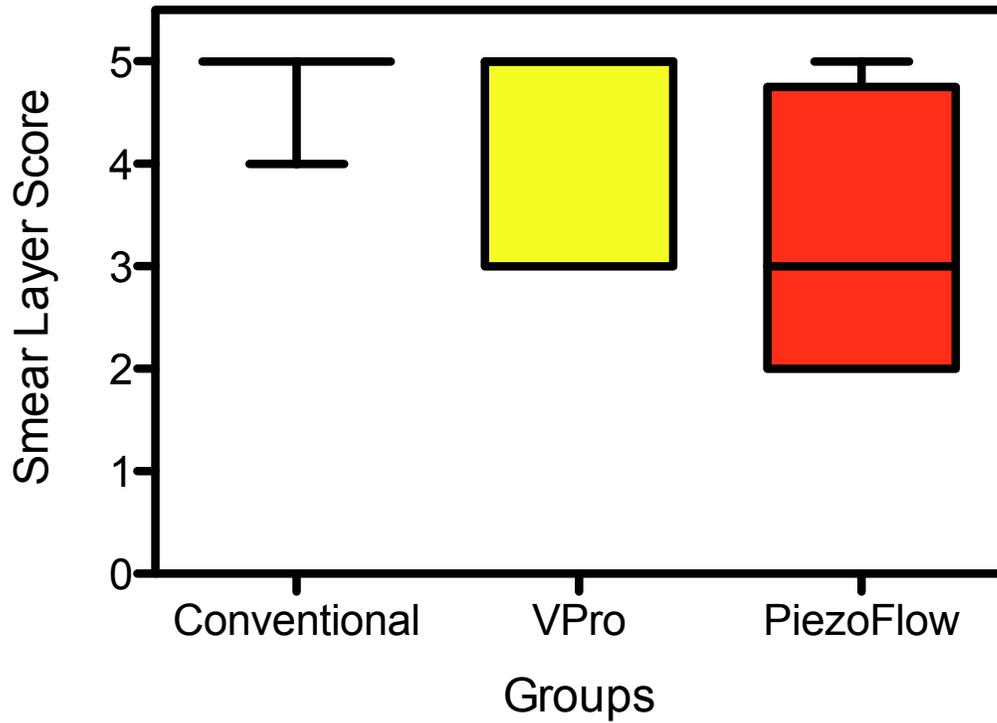


Figure 15. Smear layer score comparison among the groups at 1 mm from the apex for the straight canals
P=0.018 for PiezoFlow group.

Smear 3 mm from the apex-Straight canals

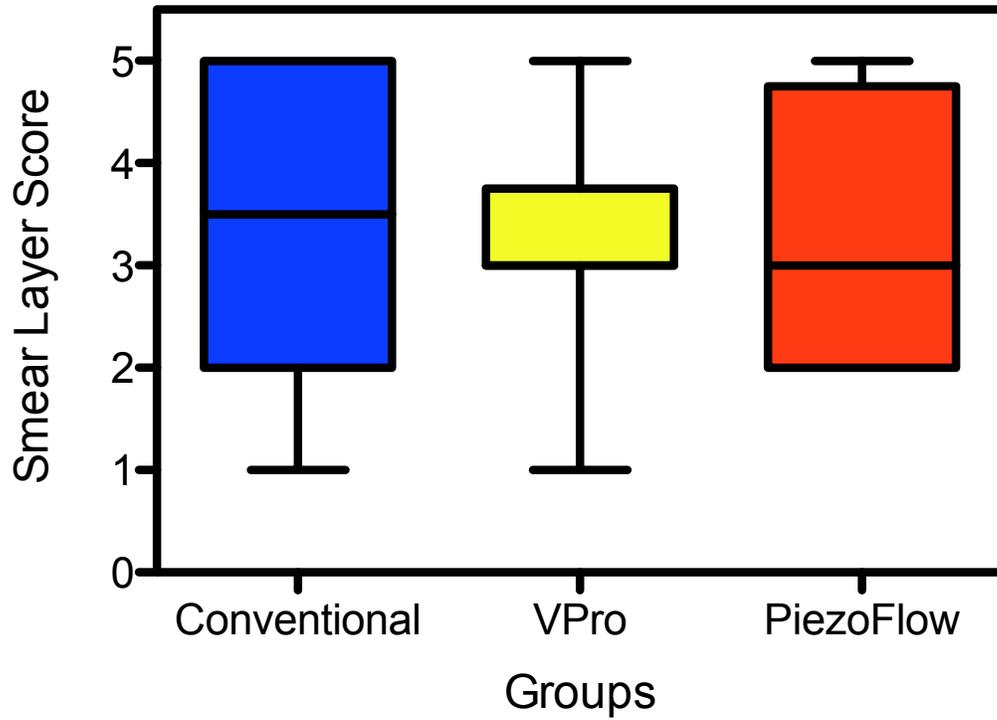


Figure 16. Smear layer score comparison among the groups at 3 mm from the apex for the straight canals. $P>0.05$

Smear 5 mm from apex-Straight canals

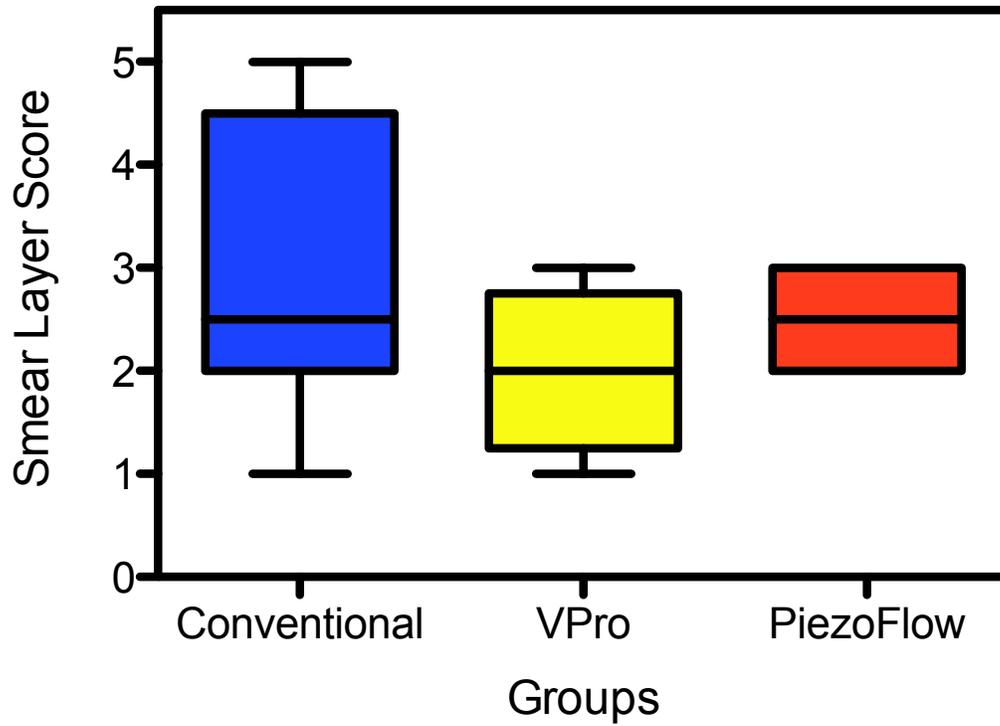


Figure 17. Smear layer score comparison among the groups at 5 mm from the apex for the straight canals. $P > 0.05$

Smear 1 mm from the apex-Curved canals

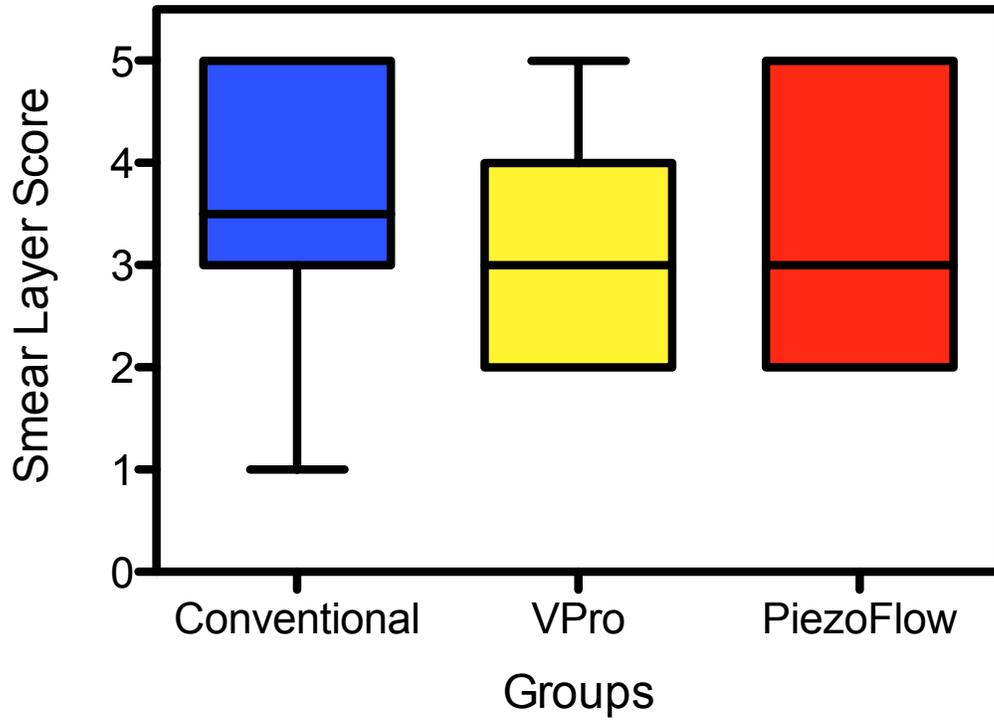


Figure 18. Smear layer score comparison among the groups at 1 mm from the apex for the curved canals.
 $P > 0.05$

Smear 3 mm from the apex-Curved canals

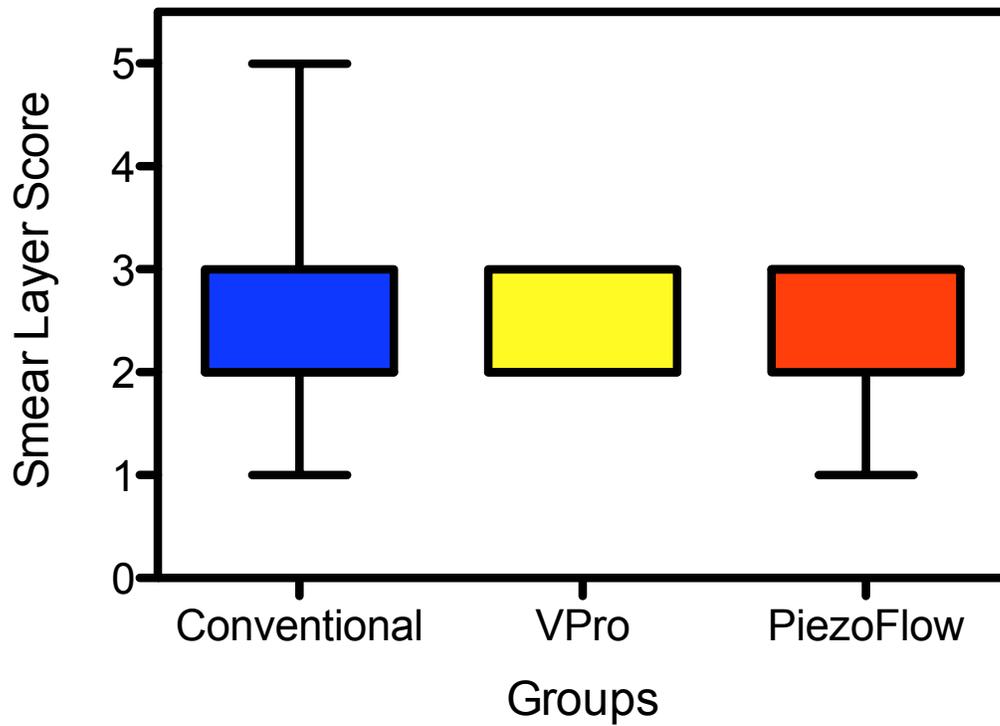


Figure 19. Smear layer score comparison among the groups at 3 mm from the apex for the curved canals.
 $P > 0.05$

Smear 5 mm from the apex-Curved canals

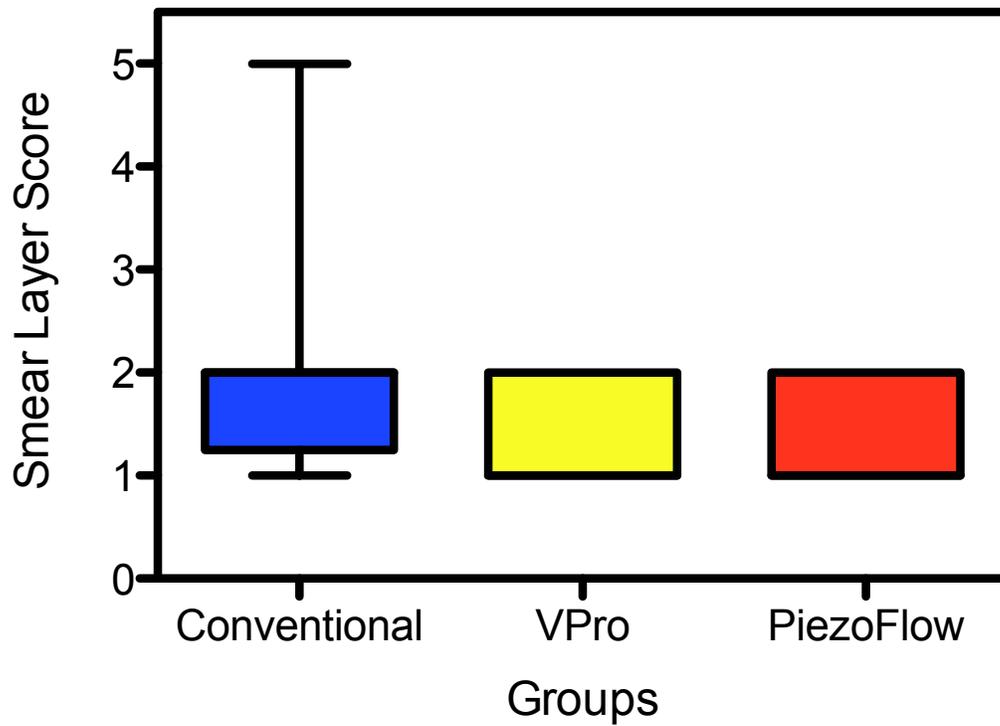


Figure 20. Smear layer score comparison among the groups at 5 mm from the apex for the curved canals.
 $P > 0.05$

Chapter 4: Discussion

The present study focused on evaluating the effectiveness of new continuous flow ultrasonic irrigation systems (ProUltra PiezoFlow and VPro StreamClean) in removing debris and smear layer after rotary instrumentation of root canals, using scanning electron microscopy. Previous studies with these types of systems have evaluated the effectiveness by bacterial reduction (Carver et al., 2007), histological analysis of canal and isthmus cleanliness (Gutarts et al, 2005; Adcock et al, 2011), and dentin groove models (Jiang et al, 2012). However, there have been no recent studies that evaluated the debris and smear layer removal by scanning electron microscopy. The literature shows support for the effectiveness of ultrasonic use in root canal debridement, however very few studies compare the differences between straight and curved canals, which this study attempted to examine. The effectiveness in curved canals is important to examine as the effectiveness of ultrasonics in these areas has been reported to be limited (Amato et al, 2011).

The study was designed to closely resemble the actual conditions encountered in routine endodontic treatment. In this study, the access cavity prepared in the teeth provided an intentional reservoir which functions to hold a more effective volume of irrigant for exchange during irrigation, which is clinically relevant. Conversely, many studies remove the crowns from the samples and this may affect the exchange of irrigants. The teeth selected for this study were freshly extracted and stored in a medium to minimize tissue breakdown. The samples were prepared as soon as possible after extraction with the hopes of having as much tissue as possible in the canals. Some studies do not take into account the history of the extracted teeth and this may affect the internal validity. Teeth that have been stored for many months in solutions with unknown chemical composition and pH may succumb to

breakdown of the tissues and degradation of the pulpal tissues and even the dentin may occur. Consequently, the results may not be valid when assessing the cleaning effectiveness of various techniques.

This was an in vitro study using extracted teeth and limitations exist with these types of studies. There is variation in the root canal morphology and standardization is difficult. The size of the canal, length of the root, and apical size was controlled as much as possible in this study. In the anterior teeth there is less variation, likely in the range of 15-20%. However, much more variation occurs in the mesial roots of the mandibular molars. In the study, two mesial canals were located and instrumented. However, in many of the samples the canals joined or had an isthmus present. It is uncertain how much of an effect this kind of variation would have had on the results but it must be considered when evaluating the data. Some of the curved canals were “double cleaned” as it was decided to apply the final irrigation to both mesial canals, therefore, canals that joined received additional ultrasonic irrigation compared to two separate mesial canals. The effect of the additional volume of irrigation and ultrasonic time must be taken into consideration. The molar groups were analyzed further and the SEM revealed the samples that had 2 separate canals or 2 canals that joined together. Statistical analysis was performed to determine if there was a difference between the teeth with canals that were separate and the teeth with canals that joined together in regards to debris removal. This was done for each of the final irrigation techniques at the 1, 3, and 5 mm level. Using a t-test, no significant differences were found between the separate or joined canals. In this study, the differing mesial root anatomy did not appear to effect the results for debris and this could be due to a threshold for cleaning that may occur with a certain volume or time of ultrasonic activation.

Another consideration is the amount of debris that is pushed into the isthmus area in the molar teeth. In this study, only the main canal wall was evaluated and the scoring may have shown relatively low debris levels in the apical 5 mm. However, a recent study showed by high-resolution micro-computed tomography scanning, that dentin debris is packed into the isthmus region after instrumentation (Endal et al, 2011). The incomplete debridement may impact the effectiveness of the treatment and future studies should incorporate this into the study design.

The teeth were coated with wax to create a closed environment that would simulate the clinical setting. This is an important consideration as Tay showed that there was a significant difference in the debridement quality of open and closed systems. Many studies have elaborate designs to create a closed system and these may provide more standardization (Susin et al, 2010). The straight and curved teeth were prepared to clinically acceptable apical preparations using .04 taper rotary instruments. A recent study evaluated the irrigant penetration in an ex vivo model (Bronnec et al, 2010). One of the conclusions was that an increased taper preparation would allow improved irrigant exchange in the apical third due to improved delivery by deeper needle penetration and by creating sufficient space for backflow of the replaced solution in the coronal direction. A future study with larger tapers may have different results with application of continuous flow ultrasonic irrigation and may aid in defining an optimal protocol for root canal debridement.

The method for determining the remaining debris in this study provides a more accurate grading as opposed to grading systems that used a 3,4, or 5 point grading scale. The Adobe Photoshop software selection tool also removes some of the subjectivity in the evaluation. This method gives the amount of remaining debris as a percentage of the total area of the

canal, thus making a better comparison of the different systems used. However, large standard deviations were observed with the debris scores and this may be partly due to this more refined grading system. For smear layer evaluation, a 5 point grading system was chosen since the criteria used by Caron gave 5 distinct categories compared to scales that used a 3 or 4 point grading system. Five readings were taken at each level using stratified randomized sampling with the goal that this method would give an accurate representation of the area being measured. Scanning electron microscopy gives excellent imaging of the internal walls of both halves of the root canal and allows for good visualization along the length of the entire root canal. However, sample preparation is tedious and the samples may be subject to contamination and artifacts. In addition, only a small part of the root canal wall is actually evaluated as only the surface is examined and the depth of the debris is not determined.

The selection of the sample size was based upon data from previous studies and a pilot study that was performed. A sample size calculator was used to obtain the number, however, it was based on anticipated means and standard deviations. The standard deviations observed in this study were higher than those anticipated and this led to the selection of a smaller sample size than should have been required. Based on calculations with the results, a sample size of approximately 15 per group would have been more appropriate.

In this study, there were no statistically significant differences in regards to the amount of debris remaining for both straight and curved canals. However, the PiezoFlow system approached significance at the 1 mm and 3 mm level in the straight canals ($p < 0.10$). One can speculate that if the sample size had been higher then statistically significant differences ($p < 0.05$) would have been observed. The VPro StreamClean appeared to be less effective

than the PiezoFlow and this was unexpected. The VPro StreamClean uses a 30 gauge needle which allows increased penetration of the needle to the apical area. The placement of the needle to the apical 5 mm should have allowed increased ultrasound energy transfer to the irrigant in this region resulting in increased streaming velocity. Several studies indicate that increased streaming velocity results in improved debridement efficiency (van der Sluis et al., 2007). A possible explanation for this observation was that the manufacturer recommended a lower power setting for ultrasonic activation of the VPro StreamClean system. Lower power results in a decrease in the intensity of acoustic microstreaming (Ahmad et al, 1987). Also, it was observed that the needle was fragile in nature as separation of the needle occurred during use and most likely this was the reason for the low power setting. The 30 gauge may also have greater contact with the root canal walls in the apical 5 mm which may have two negative effects: formation of debris and dampening of the ultrasonic energy. The PiezoFlow system is a 25 gauge needle that is meant to be inserted to only 75% of the working length. In the straight canals, which were prepared to size 40, the amount of wall contact was minor, as the needle didn't penetrate into the apical 5 mm of the canal. A medium power setting is recommended for the PiezoFlow needle and this may provide increased acoustic streaming, which may have resulted in the increased debridement that was observed. Based on the results, this combination of continuous flow irrigation and ultrasonic activation appears to be more effective in debris removal.

In the curved canals, no statistically significant differences were observed with the ultrasonic systems compared to conventional syringe irrigation. These canals were narrower and prepared to size 35 with a .04 taper while the PiezoFlow needle is equivalent to a size 50 file. Therefore, in the narrow curved canals, the penetration of this needle is limited. In

some canals, it was difficult to penetrate the needle more than 2-3 mm below the orifice before wall contact. This lack of penetration may have hindered the debridement, despite the higher ultrasonic energy that is transferred with the larger needle size. Conversely, the VPro StreamClean is able to penetrate deeper into the canal due to its size (size 31 diameter), however, more wall contact will occur which will cause increased constraint of the displacement amplitude of the file. This will lead to decreased acoustic streaming of the irrigant. Lumley recommended pre-bending of ultrasonic activated files to achieve more powerful acoustic streaming but pre-bending of the VPro StreamClean would result in breakage of the needle (Lumley et al, 1992). Even if pre-bending was possible, contact with the root canal wall is still inevitable. In addition, the VPro StreamClean can only be used at a low power setting and this would further limit any acoustic streaming in the curved canal.

In this study, there was no ultrasonic activation of the EDTA. Several studies have evaluated the activation of the EDTA to observe the effects on smear layer removal, however, agitation did not appear to improve the removal of smear layer (Chopra et al, 2008; Uroz-Torres et al, 2010). EDTA or similar chelating agents have been shown to be the most effective means of smear removal (Violich & Chandler, 2010). The goal of the continuous flow ultrasonic activation is to debride the canal as much as possible and this will facilitate smear layer removal by allowing EDTA to contact all the root canal walls. Therefore, a correlation exists between debris and smear layer. In the straight canals, only the 1 mm level had significantly less smear layer remaining compared to the conventional syringe irrigation. This could be anticipated as the debris removal at the 1 mm level approached significance. The VPro StreamClean may have potentially created smear by touching the root canal walls

in the apical 5 mm due to its penetration into this region. This may have accounted for the lack of significance in both the straight and curved canals.

An unexpected finding was the large standard deviations for the debris scores with the VPro StreamClean and the conventional syringe group. Statistical analysis between the 3 groups revealed a Bartlett's value of less than 0.01 for all groups. Bartlett's indicates a statistically significant difference among the variance of the groups. Based on this finding, it can be concluded that variances are truly different and a treatment effect was observed. The variance of the PiezoFlow, compared to the VPro StreamClean and conventional syringe irrigation, had a smaller range and was statistically significant. Therefore, the PiezoFlow was more precise in debris removal compared to the VPro StreamClean and conventional syringe irrigation. This is an important finding as it shows the repeatability of the PiezoFlow, in addition to the debris removal that approached significance ($p < .10$) at the 1 and 3 mm levels in the straight canals.

There are concerns that exist with the use of the continuous flow ultrasonic irrigation systems. Desai compared the extrusion of irrigants by 5 different irrigant delivery systems and determined that continuous flow ultrasonic irrigation had significantly more extrusion compared to EndoVac (Discus Dental, Culver City, CA), and the EndoActivator (Dentsply Tulsa Dental Specialties) (Desai & Himel, 2009). Extrusion of irrigant can lead to clinical complications during treatment. Mitchell performed a similar study and found no differences amongst the devices used (Mitchell & Baumgartner, 2011). PUI was used with intermittent flushing and this may have contributed to improved control of the irrigation, compared to continuous flow irrigation. The extent of the extrusion appeared to be more of a function of apical size. Another important consideration is the cause of iatrogenic damage within the

root canal system by an ultrasonically activated tip (Caron et al, 2010) . The potential for transportations, ledges and perforations exists with metal ultrasonic tips, especially in curved canals. The flow rate that was used for ultrasonic systems was 15 ml/min. However, there is no literature support at this point for an optimal flow rate for these systems. Initial pilot studies done by the author gave some evidence that 5 ml/min may be adequate to achieve the desired effect and this may provide improved safety without compromising the effectiveness.

Future studies of these new systems should evaluate the optimal flow rates that would be required along with varying preparations tapers and sizes. The evaluation of irrigant exchange, not only in the main canal, but in lateral canals and isthmus regions is important to assess, as it is in these regions that these systems may provide a significant advantage. An ultrasonic needle with varying needle designs may also offer advantages of safety and increased dispersion of irrigant to the lateral walls. The two needles were open ended but a needle could be tested with multiple side venting ports. Lastly, with the advent of new irrigation products such as QMix (Dentsply Tulsa Dental Specialties), the effect of ultrasonic activation, using these irrigants, may offer further advantages during treatment and this should be quantified.

Chapter 5: Conclusion

The study of root canal disinfection is expanding with a constant stream of devices being introduced to aid in the debridement of the root canal system. However, the effectiveness of these devices is often equivocal as research methodology used to evaluate the devices is difficult to standardize. In addition, it is often difficult to translate the results of laboratory studies to the clinical setting with certainty. Therefore, it is crucial to develop good experimental models that will allow testing of these new debridement and disinfection systems in a consistent and reliable manner.

Within the limitations of this study, the following conclusions were reached:

- No significant differences were detected in the ability to remove debris between the three groups. However, the PiezoFlow Ultrasonic needle approached significance at the 1 and 3 mm levels ($p=0.090$ and 0.099 respectively).
- The PiezoFlow Ultrasonic needle resulted in significantly more smear layer removal at the 1 mm level ($p=0.018$) compared to the conventional syringe in anterior teeth.
- The PiezoFlow irrigation system showed the least amount of variance for debris removal with all groups, which was statistically significant ($p<.01$) and it could be concluded that it is the most precise and predictable amongst the irrigation techniques.
- The three final irrigation techniques tested were unable to completely remove debris or smear layer from the apical 5 mm of the straight and curved root canals.

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Appendices

Appendix A

A.1 Debris Data for Straight Canals (Anterior teeth)

Debris at 1mm from apex

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3679.586	2	1839.793	2.077	.150
Within Groups	18600.393	21	885.733		
Total	22279.978	23			

Multiple Comparisons

Dunnett t (2-sided)^a

(I) Groups	(J) Groups	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
VPro	Conventional	-17.83625	14.88063	.395	-53.1072	17.4347
PiezoFlow	Conventional	-30.16250	14.88063	.099	-65.4334	5.1084

a. Dunnett t-tests treat one group as a control, and compare all other groups against it.

Debris at 3mm from apex

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2230.173	2	1115.086	2.229	.132
Within Groups	10506.283	21	500.299		
Total	12736.456	23			

Multiple Comparisons

Dunnett t (2-sided)^a

(I) Groups	(J) Groups	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
VPro	Conventional	-7.92375	11.18368	.705	-34.4320	18.5845
PiezoFlow	Conventional	-23.22500	11.18368	.090	-49.7332	3.2832

a. Dunnett t-tests treat one group as a control, and compare all other groups against it.

Debris at 5mm from apex

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	459.297	2	229.649	1.187	.325
Within Groups	4063.401	21	193.495		
Total	4522.698	23			

Multiple Comparisons

Dunnett t (2-sided)^a

(I) Groups	(J) Groups	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
VPro	Conventional	-7.00000	6.95513	.509	-23.4855	9.4855
PiezoFlow	Conventional	-10.52625	6.95513	.246	-27.0117	5.9592

a. Dunnett t-tests treat one group as a control, and compare all other groups against it.

A.2 Debris Data for Curved Canals (Mesial Root of Mandibular Molars)

Debris at 1mm from apex

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	780.993	2	390.496	.602	.558
Within Groups	12328.286	19	648.857		
Total	13109.279	21			

Multiple Comparisons

Debris at 1mm from apex

Dunnett t (2-sided)^a

(I) Groups	(J) Groups	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
VPro	Conventional	-8.50196	13.18336	.751	-40.0460	23.0421
PiezoFlow	Conventional	-14.31625	13.18336	.466	-45.8603	17.2278

a. Dunnett t-tests treat one group as a control, and compare all other groups against it.

Debris at 3mm from apex

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	110.819	2	55.409	.331	.722
Within Groups	3179.716	19	167.353		
Total	3290.535	21			

Multiple Comparisons

Debris at 3mm from apex

Dunnett t (2-sided)^a

(I) Groups	(J) Groups	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
VPro	Conventional	2.09643	6.69528	.933	-13.9235	18.1164
PiezoFlow	Conventional	-3.46929	6.69528	.829	-19.4892	12.5506

a. Dunnett t-tests treat one group as a control, and compare all other groups against it.

Debris at 5mm from apex

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	63.358	2	31.679	1.439	.263
Within Groups	396.344	18	22.019		
Total	459.702	20			

Multiple Comparisons

Debris at 5mm from apex

Dunnett t (2-sided)^a

(I) Groups	(J) Groups	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
VPro	Conventional	-3.41429	2.50822	.315	-9.4304	2.6018
PiezoFlow	Conventional	-3.90571	2.50822	.232	-9.9218	2.1104

a. Dunnett t-tests treat one group as a control, and compare all other groups against it.

Appendix B

B.1 Smear Layer Data for Straight Canals (Anterior teeth)

Smear layer at 1 mm from apex

1 mm from apex	Sample size	Sum of Ranks	
<i>Conventional</i>	8	132.5	
<i>VPro</i>	8	112.	
<i>PiezoFlow</i>	8	55.5	
<i>Kruskal-Wallis ANOVA</i>			
<i>H</i>	7.95125	<i>N</i>	24
<i>Degrees Of Freedom</i>	2	<i>p-level</i>	0.01877
<i>H (corrected)</i>	9.2084		
<i>Dunn's Multiple Comparison Test</i>			
<i>Conventional vs Vpro</i>			p < 0.05?
<i>Conventional vs PiezoFlow</i>			No
<i>Vpro vs PiezoFlow</i>			Yes
			No

Smear layer at 3 mm from apex

3 mm from apex	Sample size	Sum of Ranks	
<i>Conventional</i>	8	110.5	
<i>VPro</i>	8	105.5	
<i>PiezoFlow</i>	8	84.	
<i>Kruskal-Wallis ANOVA</i>			
<i>H</i>	0.99125	<i>N</i>	24
<i>Degrees Of Freedom</i>	2	<i>p-level</i>	0.60919
<i>H (corrected)</i>	1.14108		
<i>Median Test</i>			
<i>Overall Median</i>	3.	<i>Chi-square</i>	10.
<i>p-level</i>	0.00674		

Smear layer at 5 mm from apex

5 mm from apex	Sample size	Sum of Ranks	
<i>Conventional</i>	8	113.	
<i>VPro</i>	8	77.	
<i>PiezoFlow</i>	8	110.	
<i>Kruskal-Wallis ANOVA</i>			
<i>H</i>	1.995	<i>N</i>	24
<i>Degrees Of Freedom</i>	2	<i>p-level</i>	0.3688
<i>H (corrected)</i>	2.30346		
<i>Median Test</i>			
<i>Overall Median</i>	2.	<i>Chi-square</i>	2.
<i>p-level</i>	0.36788		

B.2 Smear Layer Data for Curved Canals (Mesial Root of Mandibular Molars)

Smear layer at 1 mm from apex

1 mm from apex	Sample size	Sum of Ranks	
<i>Conventional</i>	8	103.	
<i>VPro</i>	7	69.	
<i>PiezoFlow</i>	7	81.	
<i>Kruskal-Wallis ANOVA</i>			
<i>H</i>	0.80759	<i>N</i>	22
<i>Degrees Of Freedom</i>	2	<i>p-level</i>	0.66778
<i>H (corrected)</i>	0.85592		
<i>Median Test</i>			
<i>Overall Median</i>	3.	<i>Chi-square</i>	1.42857
<i>p-level</i>	0.48954		

Smear layer at 3 mm from apex

3 mm from apex	Sample size	Sum of Ranks	
<i>Conventional</i>	8	90.5	
<i>VPro</i>	7	75.	
<i>PiezoFlow</i>	7	87.5	
<i>Kruskal-Wallis ANOVA</i>			
<i>H</i>	0.27516	<i>N</i>	22
<i>Degrees Of Freedom</i>	2	<i>p-level</i>	0.87146
<i>H (corrected)</i>	0.33241		
<i>Median Test</i>			
<i>Overall Median</i>	2.	<i>Chi-square</i>	1.92857
<i>p-level</i>	0.38126		

Smear layer at 5 mm from apex

5 mm from apex	Sample size	Sum of Ranks	
<i>Conventional</i>	8	116.5	
<i>VPro</i>	7	73.5	
<i>PiezoFlow</i>	7	63.	
<i>Kruskal-Wallis ANOVA</i>			
<i>H</i>	2.98295	<i>N</i>	22
<i>Degrees Of Freedom</i>	2	<i>p-level</i>	0.22504
<i>H (corrected)</i>	3.81155		
<i>Median Test</i>			
<i>Overall Median</i>	1.5	<i>Chi-square</i>	3.42857
<i>p-level</i>	0.18009		