Passive ultrasonic irrigation of the root canal

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Passive ultrasonic irrigation of the root canal

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Faculteit der Tandheelkunde

This thesis is dedicated to
Antonio Nicolin
who motivated me for endodontics
and to Min-Kai Wu
my source of inspiration in endodontic research

Contents

1

General Introduction

Introduction

Apical periodontitis is an inflammatory process in the periradicular tissues caused by microorganisms in the root canal system (Kakehashi et al. 1965, Möller et al. 1981). The aim of root canal treatment is the prevention or treatment of apical periodontitis (Haapasalo et al. 2005) which includes the elimination of infection from the root canal and the prevention of reinfection (Sjögren et al. 1990). The treatment of first choice should include removal of microorganisms from the root canal system and prevention of re-infection of the root canal system *without* undermining the integrity of the root. Unfortunately, endodontic treatment without removing large amounts of tooth or root structure is not possible at this moment. Currently chemo-mechanical cleaning of the root canal system followed by filling of the root canal system is the most effective treatment strategy. However, notwithstanding the large variety of filling materials and techniques, no filling material is able to completely prevent leakage of microorganisms through the root canal system.

Chemo-mechanical cleaning includes *instrumentation* and *irrigation* of the root canal system and optional an intracanal dressing (Schilder 1974). The aim of chemo-mechanical cleaning is to remove pulp tissue (segments), microorganisms (often in biofilm) and their products (e.g. endotoxins), dentine debris or smear layer (both produced by instrumentation) from the root canal.

The root canal defines our working area and the root canal anatomy defines the complexity of this working area. Since we are not living in an ideal world, root canals are not perfectly round and smooth. In the beginning of the former century, Hess was one of the firsts to show us this complexity (Hess 1925). Irregular and oval canal cross-sections, accessory canals, isthmuses, anastomoses, fins, curves and apical delta are common features of root canal anatomy (Hess 1925, Peters 2004) (fig.: 1-3).

Figure 1(left): Example of the complicated root canal anatomy visualized by a contrast liquid in a transparent root displaying the complex anatomical structure of anastomoses and isthmuses between main canals and lateral canals
Figure 2: Cross section of an oval shaped root canal

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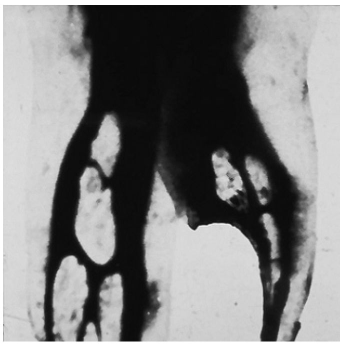
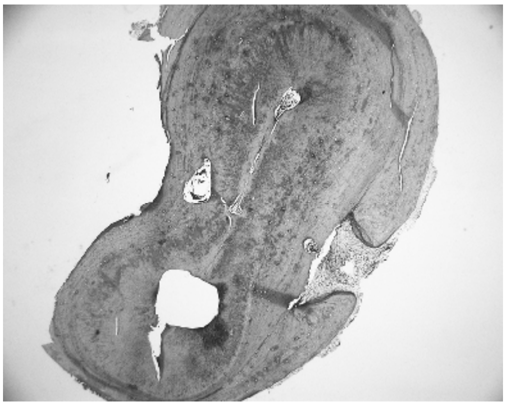


This illustrates why it is so difficult to develop endodontic treatment procedures that effectively treat apical periodontitis.

The following definition is intended to clarify the meaning of the terms ‘bacteria, microorganisms and biofilm’: biofilm is the term used to describe clusters of microcolonies of microorganisms (bacteria, yeasts, fungi, protozoa or plankton) enveloped in a slimy (glue-like) polymeric matrix of their own creation (Keevil 1998).

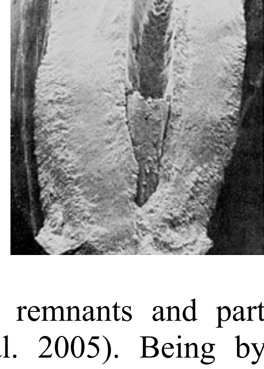
Figure 3 (right): Cross section of the apical root canal 3 mm from the apex. The MB canal is instrumented (under). The uninstrumented ML canal (above) and two extra formina (in the middle) can be seen. Histological section from the study described in chapter 12.



Instrumentation (mechanical) only does not clean the root canal

Instrumentation of the root canal implies mechanical removal of pulp tissue, dentine and or microorganisms on one hand, and the enlargement of the root canal, to shape it in a suitable form for irrigation, medicament placement (if desirable) and filling on the other hand (Hülsmann et al. 2005). Mechanical instrumentation produces a large amount of dentine chips in the root canal. Furthermore, instrumentation will result in a smear layer on the root canal wall there where an instrument has touched it (Sen et al. 1995). A smear layer is a mixture of dentine debris, remnants of pulp tissue, odontoblastic processes, and (if present) microorganisms *strongly* attached to the root canal wall (Sen et al. 1995). This layer can be 1-2 µm thick with a deeper layer that penetrates up to 40 µm into the dentinal tubules (Mader et al. 1984). Where the instrument did not touch the root canal wall, debris can be packed against the wall, in oval extensions or isthmuses, fins and in the apical part and apical delta of the root canal (apical plug) (Wu&Wesselink 2001, Hülsmann et al. 2005) (fig.: 4 and 5).

Figure 4 (Left): Cross section through an apical plug filled with tissue and dentin chips
Figure 5 (Right): Apical plug in the root canal longitudinal section



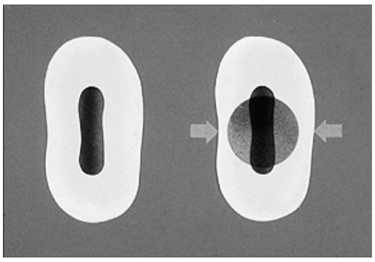
Debris may be defined as dentine chips, tissue remnants and particles *loosely* attached to the root canal wall (Hülsmann et al. 2005). Being by-products of instrumentation the smear layer and dentine debris can only be removed from the root canal by irrigation.

Instrumentation alone can not remove pulp tissue and or microorganisms completely from the root canal system due to its complexity (Hess 1925, Peters 2004, Hülsmann et al. 2005). Instrumentation is associated with instrumentation failures like zipping, ledging, perforation, instrument breakage or damage (deformation) to the apical foramen (Hülsmann et al. 2005). These failures restrict the removal of pulp tissue and or microorganisms and limit proper filling of the root canal.

In infected root canals, more microorganisms will be found close to the origin of infection and therefore more coronally than apically (Gulabivala et al. 2005). In fact in most teeth diagnosed as irreversible pulpitis, the apical part of the root canal still contains vital tissue (Trope&Bergenholtz 20002). During instrumentation, root canal instruments are always manipulated from the coronal to the apical area of the root canal, which could possibly lead to infection of the originally uninfected apical part. There are no research data available to confirm this observation and because the root canal is filled with fresh sodium hypochlorite (NaOCl) during endodontic treatment, microorganisms could be dissolved or eliminated immediately in the irrigant during transportation to the apical root canal. However, when infected root canal instruments, penetrate the periapical tissue through the apical foramen, on purpose or by accident, inoculation of microorganisms or infected debris in the periapical tissue can occur (Hülsmann et al. 2005). This is often associated with post endodontic treatment disease (Siquera 2005). Furthermore instrumentation weakens the tooth structure by removing dentine from the inner side of the root canal (Trope&Ray 1992, Zandbiglari et al. 2006)

When the root canal cross-section is oval shaped, the instruments probably have a difficult time to reach the complete canal wall and common instrumentation techniques leave uninstrumented wings where micro-organisms and debris can remain (Wu&Wesselink 2001, Peters 2004). An increase in instrument size aiming to solve this problem can result in perforation or excessive removal of root structure (fig.: 6).

Figure 6: Increasing the instrument size does not solve the problem



It was assumed that the circumferential filing technique could completely clean the root canal wall by using a small file scraping it. This could be an alternative instrumentation technique for the treatment of oval root canals. However some authors state that circumferential filing is unable to touch the complete root canal wall (Evans et al. 2001) which was confirmed by a study of Wu et al. (2003) (second chapter).

From the above mentioned observations the function and limitation of instrumentation is explained. The only rational motive for instrumentation is to create space for irrigation and to create a shape suitable for a (temporary) root canal filling.

Intracanal dressing (chemical)

In addition to instrumentation and irrigation, dressing of the root-canal for 1 week with calcium hydroxide ($Ca(OH)_2$) has been shown to increase the percentage of micro-organisms -negative teeth to around 70% (Law & Messer 2004). By extrapolation, the regimen including $Ca(OH)_2$ dressing between appointments (two visit endodontics) should provide a higher healing rate of apical periodontitis than one visit endodontics (without $Ca(OH)_2$ dressing), because microorganisms could be further reduced. However this hypothesis is not supported by research (Weiger et al. 2000, Peters&Wesselink 2002, Sathorn et al. 2005). $Ca(OH)_2$ is only effective when in close contact with microorganisms (Siqueira&Lopes 1999). This condition is difficult to accomplish because the complex root canal anatomy makes it impossible to completely remove smear layer or debris from oval canal extensions, irregularities, isthmuses and anastomoses from the root canal. Therefore its effect is unpredictable. $Ca(OH)_2$ does not kill all bacteria (Siqueira&Lopes 1999) and is not effective against E. Faecalis, which is frequently associated with endodontic failures (Sundqvist et al. 1998). Which product could kill all root canal bacteria is unknown. Furthermore it is difficult to remove $Ca(OH)_2$ completely from the root canal which could effect the sealing ability of the root canal filling (Margelos et al. 1997, Lambriandis et al. 2006).

Because intracanal dressing is not a reliable tool for disinfection of the root canal irrigation remains indispensable for thorough root canal disinfection.

Irrigation (mechanical and chemical)

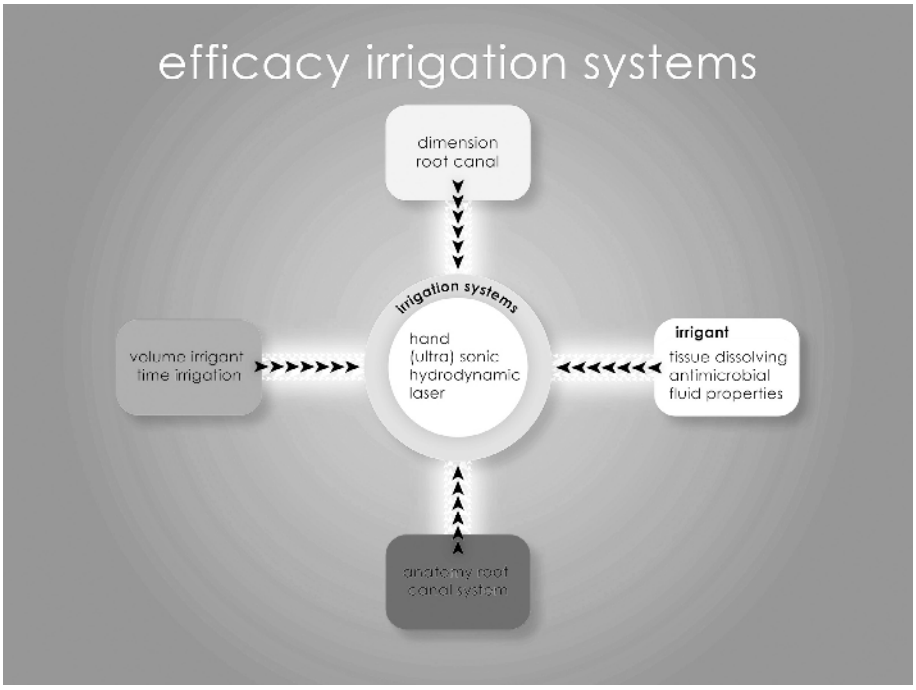
Because instrumentation and chemical dressing can not effectively clean and disinfect the root canal, cleaning and disinfection rely on irrigation. Irrigation of the root canal system enables the irrigant to be active in the root canal system (chemical) and to flush pulp tissue and or micro-organisms (planktonic or biofilm) out of the root canal system (mechanical).

The aim of irrigation of the root canal system is to remove pulp tissue and or micro-organisms (planktonic or biofilm), smear layer and dentine debris (by products of instrumentation) from the root canal system (Haapasalo et al. 2005), neutralize endotoxins and other microbial elements and lubricate canal walls and instruments (Schäfer 2007).

Although it is widely acknowledged that irrigation is indispensable during endodontic treatment, many aspects of irrigation are still unknown. A critical evaluation of the existing knowledge is reported below.

Irrigation systems supply energy to the irrigant in the root canal and are the heart of the irrigation process because they pump the irrigant through the root canal system, like the heart pumps the blood through the circulation. Without energy transfer, the irrigant will not flow in the root canal. The energy transfer mechanism determines the specific working mechanisms of the irrigant. During *hand* irrigation, the irrigant flows in the canal because the *hand* exercises pressure to the plunger of the syringe and this pressure will determine the energy of the flow. During sonic irrigation the frequency and intensity of the sonically oscillating wire in the irrigant will determine the streaming velocity of the irrigant and therefore the cleaning efficacy of the irrigant. The differentiation between irrigation systems is based on the mechanism of energy transport to the irrigant. Factors influencing the efficacy of irrigation systems are: the type of irrigant, root canal anatomy, dimension of the root canal, volume of the irrigant and time of the irrigation (fig.: 7). Because hand irrigation is the most common endodontic irrigation system, the influencing factors are discussed in relation to hand irrigation. The passive ultrasonic irrigation of the root canal is the main topic of this thesis and therefore a short introduction is given in this chapter.

Figure: 7 Schematic representation of the factors influencing the efficacy of the irrigation systems



Hand irrigation

Hand irrigation is the most popular irrigation system of the root canal. During hand irrigation, the irrigant is supplied to the root canal with a syringe and a needle attached to it (fig.: 8). The energy is transferred to the irrigant by the force exercised by the hand (finger) of the operator to the plunger. This force and the length and diameter of the needle will determine the energy of the flow of the irrigant when it leaves the tip of the needle. Needles are available in different sizes and the diameter is indicated in gauge, e.g. 26 gauge = 0.4 mm and 27 gauge is 0.36 mm. The needle should move freely in the root canal to permit the reverse flow of irrigant from the needle to the coronal root canal and to prevent the irrigant from being pushed through the apex of the root in the periapical tissue, which can result in a severe tissue reaction. The reverse flow is important for the efficacy of hand irrigation probably more for the mechanical as for the chemical component.

The efficacy of hand irrigation consists of two components:

- mechanical component: flushing action, important for the removal of pulp tissue, microorganisms and debris
- chemical component: tissue dissolution and antimicrobial properties

Figure 8 Syringe and needle are indispensable for hand irrigation

The shorter the time used to empty the syringe, the higher the pressure on the plunger. This pressure is defined as the force (P) on the plunger applied over a certain surface area (S), P = F/S (Pashley et al. 1981). The pressure at the tip of the needle will be significantly smaller than just under the plunger due to a pressure fall caused by the diameter and the length of the needle. The thinner the diameter of the needle and the longer the needle the higher the decrease of pressure. The flow rate of the irrigant will be determined by the difference of the pressure at the tip of the needle and the pressure in the root canal. Because the pressure just beyond the tip of the needle is almost atmospheric (Tilton 1999) the flow rate of the irrigant will be low. The flow rate will determine the mechanical component of the irrigation, the flushing effect. The lower the flow rate, the lower the flushing effect.

In the study of Chow et al. (1983) a 25-gauge needle (0.455 mm) was more effective than a 23-gauge needle (0.573 mm) in removing inorganic particles from the root canal. Because the pressure on the plunger was standardised, the flow rate was lower for the 25-gauge needle, indicating that within certain limits the flow rate is less important than the depth of the needle insertion because the smaller needle could penetrate deeper in the root canal. The tissue-dissolving component was excluded because inorganic particles and saline were used.

The importance of the tissue dissolving effect of NaOCl during hand irrigation was illustrated by an in vivo study of Rosenfeld et al. (1978). In this study a 5.25% solution of NaOCl dissolved vital pulp tissue for a mean distance of 1.7 mm from the needle in the coronal root canal and 0.57 mm from the needle in the apical root canal, while saline did not remove any pulp tissue. The diameter of the needles was standardised resulting in comparable flow rates and saline does not dissolve pulp tissue.

This indicates that for the mechanism of hand irrigation the tissue dissolving effect of NaOCl is more important than the flow of the irrigant, when the removal of pulp tissue is concerned (chemical) and that depth of needle insertion is more important for the flushing effect (mechanical) than the energy of the flow, because the flow in se is low.

irrigants

The most common root canal irrigants currently available are: sodium hypochlorite (NaOCl), chlorhexidine (CHX), hydrogen peroxide (H_2O_2), iodine potassium iodine (IPI) and MTAD (a mixture of tetracycline (doxycycline, 3%), citric acid (4.25%), and detergent (Tween 80, 0.5%)). Sodium hypochlorite is the most effective endodontic irrigant because it is the strongest oxidator of them all and therefore it is a strong solvent of organic tissue, has good antimicrobial properties, inactivates endotoxins, acts as a lubricant and is non toxic (Moorer&Wesselink 1982). Other irrigants like CHX, IPI , H_2O_2 or MTAD have not been proven to be more effective than NaOCl (Schäfer 2007). The main disadvantage of these irrigants is the low or absent tissue dissolving potential (Zehnder 2006), which is indispensable due to the complexity of the root canal system. The antimicrobial effect of H_2O_2, IPI and MTAD is questionable (Schäfer 2007). NaOCl seems to be the most effective irrigant in destructing the biofilm compared to the other available irrigants (Clegg et al. 2006). However, because studies on in vitro biofilm in the root canal are still in an experimental stage, it is difficult to draw hard conclusions from these studies.

Surprisingly, despite widely studied, the actual mechanism of action of NaOCl is not fully known (McDonnel&Russell 1999). When NaOCl is dissolved in water, the following reaction will occur NaOCl + H_2O → HOCl + Na^+ + OH^- and the pH of water will increase (Moorer&Wesselink 1982). HOCl (hypochlorite acid) can divide into OCl^- (hypochlorite) and H^+. The 'available chlorine' in any hypochlorite system is the sum of the HOCl and OCl^- (Moorer&Wesselink 1982). Between pH 4 and 7, chlorine exists predominantly as HClO, whereas above pH 9 OCl^- dominates (McDonnel&Russell 1999). NaOCl is a highly active oxidizing agent and thereby destroys the cellular activity of proteins (McDonnel&Russell 1999). HOCl has long been considered as the active part, responsible for bacterial inactivation by NaOCl, the OCl^- ion having a minute effect compared to undissociated HOCl. This correlates with the observation that NaOCl activity is greatest when the percentage of undissociated HOCl is highest (McDonnel&Russell 1999). NaOCl is effective against bacteria, viruses and fungi (Chaidez et al. 2003, Ruff et al. 2006). Heated NaOCl disintegrates at 40ºC and can partially split into sodium (Na^+), hypochlorite (ClO^-), sodium hydroxide (NaOH), hypochlorite acid (ClOH), chlorine (Cl_2), oxygen (O) or sodium chloride (NaCl).

No consensus has been reached on the optimal concentration of the NaOCl solution as an endodontic irrigant and presently concentrations of 0.5% – 5.25% are propagated. An increase in *temperature* of NaOCl results in an increase in tissue dissolving potential and antimicrobial properties (Zehnder 2006). An increase of the *concentration* of NaOCl will result in an increase in the tissue dissolving potential. Effective refreshment and agitation of NaOCl are more important than a higher concentration for its tissue dissolving potential (Moorer&Wesselink 1982) and a concentration of 0.5% is enough for an efficient antimicrobial effect on planktonic bacteria (Zehnder 2006). The effect of the concentration on the biofilm is not known. Furthermore a 5.25% solution significantly decreases the elastic modulus and flexural strength of human dentin compared to physiologic saline, while a 0.5% solution does not (Zehnder 2006). But if a higher concentration combined with effective refreshment will dissolve more organic tissue in the *remote areas* of the root canal system is not known. Arguments against a high concentration (5.25% or higher) are the increased toxicity, which could result in more severe side effects when NaOCl is accidentally extruded in the periapical tissues. However, no research data are available to confirm this. The complex anatomy of the root canal system could be a motivation to use the highest concentration possible to strive for maximum tissue dissolution in the fins, anastomoses, isthmuses and lateral canals. The more confined the area of organic tissue, the more difficult the organic tissue can be dissolved and perhaps the more important a higher concentration could be. However, this supposition has not yet been confirmed by research.

Fluid properties

Fluid properties, like viscosity or surface tension could have an influence on the flow rate or contact area between on the one hand the irrigant and on the other hand the content of the root canal and the root canal wall. Higher viscosity could increase the flow rate of the irrigant, however no information is available on this subject in the endodontic literature. A lower surface tension of the irrigant could increase the dentine wetting ability (Cunningham et al. 1982, Abou-Rass et al. 1982, Zehnder et al. 2005). Addition of alcohol or a wetting agent could reduce the surface tension of the irrigant (Cunningham et al. 1982, Abou-Rass et al. 1982, Zehnder et al. 2005). These agents however decrease the amount of free chlorine in NaOCl thereby reducing the antimicrobial and tissue dissolving capacity. This reduction could be far worse than the effect of the reduced surface tension. Zehnder and coworkers (2005) even concluded that endodontic chelator solutions with a lowered a surface tension did not remove more calcium from the root canal walls of instrumented root canals. The effect of the hydrophilic properties of dentine could be more important than a reduced surface tension (Zehnder et al. 2005).

An air bubble in the root canal could have a negative influence on the flow of the irrigant in the root canal by blocking it (Chow et al. 1983). When an air bubble is more apical in the root canal than the deepest point of the needle, the air bubble will withhold the flow of irrigant apical from the air bubble. Because the presence of air bubbles is unpredictable, it can influence the efficacy of the irrigation without knowing.

volume

The volume of irrigant possibly influences the effect of hand irrigation. The volume of irrigant has to be sufficient to refresh effectively the NaOCl in the root canal (chemical: antimicrobial, tissue dissolution) and to flush actively the content out of the root canal (mechanical). The amount of pulp-tissue, microorganisms and debris in the root canal will determine the amount of NaOCl needed. This amount can never be established. It can be assumed that an increase in the volume of the irrigant is associated with more effective cleaning of the root canal (Baker et al. 1975, Sedgley et al. 2004). The focus of these two studies was the influence of the volume of NaOCl on the efficacy of the flushing effect of the irrigant (mechanical) and not on the efficacy of the chemical aspect (tissue dissolving properties) which was never studied. However, no significant difference could be seen in the removal of dentine debris from a groove in the apical root canal whether 2 mL or 10 mL of a 2% solution of NaOCl was used (van der Sluis et al. in progress). Since during hand irrigation the flow rate is low and only loose debris can be removed, more than 2 mL does probably not make much of a difference. A flush of 2 mL of NaOCl after every file used and a final flush of 10 ml is generally advised (Yamada et al. 1983) but without sufficient scientific background.

time of irrigation and working time of irrigant

Time of irrigation and working time of irrigant in the root canal will probably influence the efficacy of the irrigant because it will influence the chemical effect on the biofilm and the mechanical effect of the flushing. It is impossible to give advice on the irrigation time because no data are available (Zender et al. 2006). Some data of in vitro studies using a biofilm model, suggest a contact time of 60 minutes to destroy a biofilm in vitro (Spratt et al. 2001). But in another study a biofilm was destroyed within 5 minutes using 6% or 1% NaOCl (Dunavant et al. 2006). It is unknown if these data can be extrapolated to the clinical situation.

dimension of the root canal

The dimension of the root canal determines the efficacy of hand irrigation, mainly because a larger dimension will result in a deeper penetration of the needle of the syringe (Senia et al. 1971, Abou-Rass et al. 1982, Albrecht et al. 2004, Usman et al. 2004, Khademi et al. 2006).

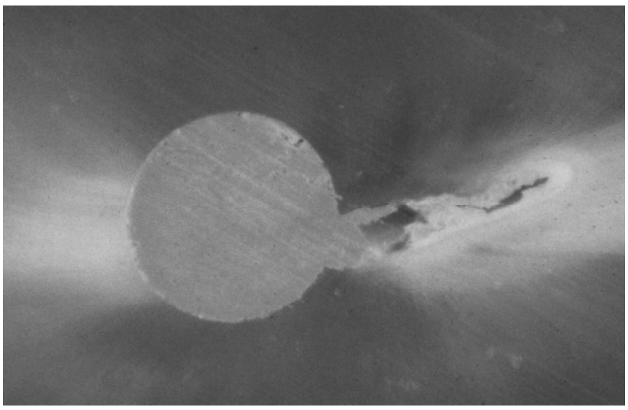
The dimension of the root canal will also influence the flow rate of the irrigant. When the root canal is too large a turbulent flow could occur which stops the laminar reversible flow of the irrigant. This will disturb the flushing effect (Hsieh et al. 2007). The curvature of the root canal could influence the efficacy of hand irrigation because it could hamper the flow of irrigant in the root canal. The only information available of the influence of the canal curvature on the efficacy of hand irrigation is the recently published article of Nguy et al. (2006). In their study the influence of three different root curvatures (straight, 15º-19º and 24º- 28º) and three different preparation sizes (size 27/taper .04; size 36/taper .04; size 46/ taper .04) were evaluated on the efficacy to remove planktonic bacteria (bacteria not grouped in a biofilm) from the root canal by hand irrigation. Only in the group with the severe curvature (24º- 28º) significant more planktonic bacteria were removed from size 46, taper 0.04. canals than size 27 taper 0.04 canals.

An advantage of hand irrigation is the control of needle insertion in the root canal, apical refreshment and volume of irrigant. The disadvantage is the restricted flow rate which will limit the effect of hand irrigation to the removal of loose debris from the root canal.

Consequences of hand irrigation

In oval canals, the lateral compaction technique of cold gutta-percha or the vertical compaction technique of warmed gutta-percha, resulted in defective fillings and unfilled spaces in the apical regions (fig.: 10) (Wu & Wesselink 2001, Wu et al. 2001). Remaining dentine debris, which was not removed by chemo-mechanical cleaning combined with handirrigation, was the main cause of these defective fillings. Eventually this can compromise the seal of the root canal filling because microorganisms or nutrition for microorganisms can leak through the non-homogeneous mass of dentine debris (study chapter 4). This seal is crucial because the purpose of a root canal filling is to prevent the influx of microorganisms or nutrition for microorganisms left in the root canal after chemo-mechanical cleaning. Because the oval canal is common in the apical part of the root canal this can be considered as a problem (Wu et al. 2000).

Figure 10 Defective gutta-percha root filling because of remaining dentine debris in an oval root canal extension



Also the removal of microorganisms from the root canal is a problem. The in vivo studies of Ricucci et al. (2003) and Naïr et al. (2005) show that hand irrigation can not remove all the microorganisms from the apical root canal. In these studies chemo-mechanical cleaning was combined with hand irrigation during the endodontic treatment. The teeth were extracted because of failure (Ricucci et al. 2003) or the apical root was removed after treatment (apical surgery) with the purpose to evaluate the cleaning efficacy of the endodontic treatment (Naïr et al. 2005). The roots were decalcified and longitudinal- and vertical sections were cut and stained and evaluated with light or SEM microscopy. Microorganisms could still be found after root canal treatment in the apical part of the root canals. These remaining microorganisms could induce apical periodontitis or hamper healing of apical periodontitis.

Hand irrigation is unable to remove $Ca(OH)_2$ completely from the root canal (Margelos et al. 1997, Kim & Kim 2002, Hosoya et al. 2004, Lambriandis et al. 2006). $Ca(OH)_2$ remnants left in the root canal can result in a thicker non-homogenous appearance of root canal sealers which will influence the properties of the sealer (Margelos et al. 1997, Kim & Kim 2002, Hosoya et al. 2004). The $Ca(OH)_2$ remnants can also result in a chemical reaction with the sealer resulting in a reduction of flow or working time (Margelos et al. 1997, Hosoya et al. 2004). Cracks were visible in zinc-oxide eugenol sealer after the use of $Ca(OH)_2$ (Kim & Kim 2002) which can be explained by the faster setting of the sealer under the influence of $Ca(OH)_2$ (Margelos et al. 1997). $Ca(OH)_2$ remnants could also prevent sealer from penetrating the dentinal tubules resulting in a potential reduction in sealer adaptation to the root canal wall (Çalt & Serper 1999). The dimensional instability of $Ca(OH)_2$ and its potential to dissolve in water and dissociate into hydroxide and calcium ions (Cohen & Burns 2002) could influence the leakage of root fillings on the long term. All these factors could influence the sealing of the root canal filling. This has never been confirmed by leakage tests because $Ca(OH)_2$ decolourises methylene blue, often used as indicator in leakage tests, and it would be more interesting to evaluate the leakage some time after filling to detect the influence of the dissolved $Ca(OH)_2$ and the long term effect on the sealer.

Conclusion: Hand irrigation with NaOCl and EDTA does not effectively remove pulp tissue, micro-organisms, smear layer, debris or $Ca(OH)_2$ from the root canal system (Wu&Wesselink 2001, Ricucci et al.2003, Peters 2004, Naïr et al.2005, Lambriandis et al. 2006).

Passive ultrasonic irrigation (PUI) and influencing factors

In a study were oval root canals were irrigated before filling with PUI, the root canals could be filled almost completely, no areas of remaining dentine debris were seen (Ardilla et al. 2003). This indicated that PUI was more effective in removing dentine debris than hand irrigation. The study of Lee et al. (2004) supported this observation, showing that PUI was more effective in removing dentine debris from an artificially groove in the apical root canal than hand irrigation.

Passive ultrasonic irrigation (PUI), is the ultrasonic activation of an irrigant in the root canal, using an ultrasonically oscillating small file or smooth wire (e.g. size:15, 20) placed in the centre of the root canal, after the root canal has been shaped up to the master apical file (Ahmad et al. 1987). Because the root canal has been enlarged, the irrigant can flow in the root canal and the file or wire can vibrate relatively freely, which will result in more powerful acoustic streaming (Ahmad et al. 1987). Passive ultrasonic irrigation (PUI) with sodium hypochlorite (NaOCl) as the irrigant, removes more dentine debris, planktonic bacteria and vital pulp tissue from the root canal than hand irrigation (Huque et al.1998, Lee et al. 2004, Gutarts et al. 2005). During PUI more dentine debris can be removed from the isthmus, oval extensions in the root canal and irregularities from the root canal wall (Goodman et al. 1985, Lee et al. 2004).

PUI seems to be a promising irrigation system to add at the end of the root canal treatment. However, it is not very clear how PUI should be used. The factors which influence hand irrigation like the choice of irrigant, the flow and volume of the irrigant, the time of irrigation and working time of irrigant, the dimension of the root canal, could also influence PUI.

Aim and outline of the thesis

The aim of this thesis was:

- to evaluate if the circumferential filing technique is more effective than a rotation techniquein cleaning the walls of oval root canals
- to evaluate if instrumentation of root canals affects the resistance to root-fracture
- to evaluate if the quality of root canal fillings in oval root canals is comparable to rootcanal fillings in round canals
- to evaluate if the reliability of the clinical taken radiograph is less in oval shaped canals than round canals
- to evaluate if passive ultrasonic irrigation could improve the sealing of root canal fillings in oval root canal
- to review the literature on passive ultrasonic irrigation (PUI)
- to evaluate if a smooth wire is as effective as a cutting file in removing dentine debris from the root canal
- to evaluate if the diameter and taper of the root canal have an influence on the dentine debris removal from the root canal during PUI
- to evaluate if a continuous flush method is as effective as an intermittent flush method during PUI and to evaluate the influence of time and volume of irrigant on the efficacy of dentine debris removal from the root canal during PUI
- to evaluate if water is as effective as NaOCl during PUI
- to evaluate if the organic tissue dissolving potential of NaOCl is the reason for the efficacy of NaOCl as irrigant during PUI
- to evaluate if PUI is effective in removing Ca(OH)2 from the root canal.

Outline of the thesis.
In chapter one a general introduction and the aim of the thesis has been defined. In chapter two the efficacy of the circumferential filing technique and the balanced force technique in oval root canals has been described and in chapter three the influence of instrumentation of the root canal on the resistance to vertical root fracture is discussed. The difference and diagnosis of the quality of root fillings in round and oval canals is evaluated in chapter four. Because one of the conclusions from the before mentioned studies is that instrumentation combined with hand irrigation is unable to clean effectively oval root canals, a study was undertaken to evaluate the influence on the sealing quality of root fillings in oval root canals after ultrasonic irrigation (chapter five).

Because ultrasonic irrigation seems to be more effective in removing dentine debris from oval root canals, a literature review on passive ultrasonic irrigation was undertaken which is described in chapter six.

During PUI often a cutting file is used because smooth wires specially developed for this purpose are not yet widely available. The disadvantage of a cutting file during PUI is damage of the root canal wall and apical perforation. Therefore, chapter seven evaluates the effectiveness of dentine debris removal from the root canal comparing a smooth wire and a cutting K file. As described in the introduction the dimension of the root canal influences the efficacy of pulp tissue and dentine debris removal from the root canal. If this also concerns PUI is not known and is described in chapter eight. Little information is available on the influence of volume of irrigant, time of irrigation on the efficacy of hand irrigation. The same goes for PUI. Therefore the influence of type of irrigant, time of irrigation, volume of irrigant, irrigant application on dentine debris removal from the root canal are discussed in chapter nine and ten. Calcium-hydroxide ($Ca(OH)_2$) is widely used as temporary filling material between two sessions of a root canal treatment. Since PUI is more effective in dentine debris removal from the root canal than hand irrigation, an evaluation of the efficacy to remove the intermittent filling material $Ca(OH)_2$ from the root canal is described in chapter eleven. The result could also give more information on the mechanisms of PUI. If PUI is also effective in the removal of pulp tissue from the root canal is described in chapter twelve.

2

The capability of two hand instrumentation techniques to remove the inner layer of dentine in oval canals

In International Endodontic Journal 2003; **36**, 218-24.
M.K. Wu, L.W.M. van der Sluis, P.R. Wesselink.

Abstract

Aim To evaluate the capability of two hand instrumentation techniques, namely balanced force and circumferential filing, to remove the inner layer of dentine in oval canals.
Methodology Thirty mandibular incisors with a single oval canal were selected and divided into two equal groups on the basis of their radiographic bucco-lingual internal diameters measured at a level 5 mm from the apex. Two different hand instrumentation techniques, i.e. balanced force and circumferential filing, were used in each group. A modification of the Bramante muffle mould was used to examine the root canal before and after instrumentation at a level 5 mm from the apex. The two images of the root cross-section before and after instrumentation were superimposed on one another. The perimeter of the canal and the length of the arc where the inner layer of dentine had been removed by the instrumentation were measured by means of an image analysis program. The percentage of this arc was calculated.
Results The balanced force method removed the inner layer of dentine from 38.6% of the circumference of the canal wall, as opposed to 57.7% using circumferential filing. The difference was not statistically significant ($p=0.101$).
Conclusion In oval canals, both the balanced force and circumferential filing techniques left large portions of the canal wall uninstrumented.

Introduction

In infected root canals, the inner layer of dentine may contain microorganisms (Peters et al. 2001). One aim of root canal instrumentation is to remove the inner layer of dentine from all aspects of the root canal wall (Walton & Torabinejad 1996). However, in many cases bacteria have penetrated deeply into the dentine (Armitage et al. 1983, Ando & Hoshino 1990, Peters et al. 2001), making it difficult to completely remove them from the dentinal tubules using instruments. Moreover, it would be more difficult to remove the entire inner layer of dentine in long oval root canals than in round (Wu & Wesselink 2001).

In many dental schools, students are taught that the apical root canal should be enlarged to three sizes larger than the first file that binds at the working length (the first binding file) (Weine 1996). The aim of this procedure is to remove the entire inner layer of dentine from the apical canal wall. The first binding file is the smallest instrument that enables dentists to feel resistance at or before reaching the working length. It is thought that this file can gauge the apical diameter, so that after enlargement using three larger files, the inner layer of dentine together with the microorganisms can be removed from the entire wall.

In a recent study (Wu et al. 2002), however, it was found that at its working length the first binding file touched only one side of the wall in 75% of curved canals, and failed to touch any wall in the other 25%. This indicates that after further enlargement the inner layer can be removed from one side of the wall only. Whether the inner layer can be removed from the entire canal wall remains questionable.

Large master files have been recommended in the past to scrape the entire circumference of the root canal wall (Tronstad 1991). For instance, sizes 70–90 have been recommended for all maxillary central incisors. The internal diameter of maxillary central incisors may vary from 0.19 to 0.94 mm, 2 mm from the apex (Wu et al. 2000b); at this level the diameter of a size 90 master file is 0.92 mm. Clinically, dentists do not know whether the canal is 0.19 or 0.94 mm, and using large files in all maxillary central incisors could unnecessarily result in a severe weakening of those small roots (Trope & Ray 1992). Furthermore, using large files in curved roots can lead to apical lacerations and ledging (Tang & Stock 1989, Briseno & Sonnabend 1991, Nagy et al. 1997, Buchannan 2000, Wu et al. 2000a). Some textbooks say that curved canals should not be prepared apically beyond a size 20 or 25 (Ingle et al. 1994, Walton & Torabinejad 1996). The use of Ni–Ti rotary instruments can reduce, but not completely prevent, the occurrence of apical transportation (Wu et al. 2000a, Hülsmann et al. 2001). This means that using large files can weaken the root and increase the risk of apical transportation.

Oval-shaped canals, most of which have long bucco-lingual but short mesio-distal diameters, exist in 25% of roots (Wu et al. 2000b). Using a larger file in long oval canals in order to include the entire oval canal in the preparation can result in perforation of the mesial or distal wall, as suggested by Wu & Wesselink (2001). It has been supposed that a circumferential filing technique with a small file will prevent this, while completely scraping the wall. However, several studies have shown that circumferential filing is not capable of contacting the entire canal wall (Reynolds et al. 1987, Zuolo et al. 1992, Siqueira Jr et al. 1997, Evans et al. 2001). Access cavity location and design may influence the percentage of the wall surface that is contacted by the instruments. However, Mannan et al. (2001), who used different cavity designs in maxillary anterior teeth, found that regardless of access cavity design, mechanical preparation using stepback filing did not allow instrumentation of the entire wall.

The balanced force technique (Roane et al. 1985) has been used in the preparation of curved root canals (Wu & Wesselink 1995). However, it has been found that in two-thirds of oval canals use of the balanced force method left a portion of the root canal wall uninstrumented (Wu & Wesselink 2001).

Different methods have been used to evaluate the cleaning efficacy of root canal preparation. Histological cross-sections have been used and the capability of different techniques to remove predentine evaluated (Reynolds et al. 1987, Zuolo et al. 1992, Siqueira Jr et al. 1997, Evans et al. 2001). However, predentine was not always visible (Evans et al. 2001). Longitudinal sectioning allows for an evaluation of the entire root surface (Lumley et al. 1993, Wu & Wesselink 1995). However, the root surface can be evaluated only once, after the root canal preparation. The muffle model introduced by Bramante et al. (1987) made it possible to examine the root canal both before and after instrumentation, at any level within the same canal system. Since then, various modified versions of this model have been used to evaluate the effects of root canal instrumentation (Calhoun & Montgomery 1988, McCann et al. 1990, Sydney et al. 1991, Hülsmann et al. 1999, 2001).

The purpose of this study was to use a muffle model to evaluate the capability of two hand instrumentation techniques, i.e. balanced force and circumferential filing, to remove the inner layer of dentine in oval canals.

Materials and methods

From a pool of extracted human permanent teeth stored in 5% formol-saline, 30 mandibular incisors with a single canal were selected after mesio-distal radiographs indicated a bucco-lingual internal diameter of 0.6–1.2 mm at a level 5 mm from the apex. Since the average mesio-distal internal diameter was found to be 0.3 mm at the same level (Wu et al. 2000b), all these teeth had a single oval-shaped root canal. These 30 teeth were of approximately the same length. They were divided into two equal groups (n = 15) on the basis of their bucco-lingual internal diameters. One of two different hand instrumentation techniques, i.e., balanced force or circumferential filing, was used in each of these groups.

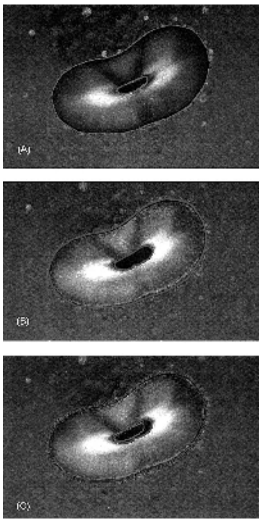
A modified version of the muffle mould technique (Bramante et al. 1987) was used in which the root of each tooth was embedded in acrylic resin (Vertex, Dentimex, the Netherlands). Grooves in the walls of the mould allowed removal and exact repositioning of the complete tooth-block or sectioned portions of the tooth (fig.: 1).

Figure 1 Grooves in the walls of the muffle mould (A) allowed removal and exact repositioning of the complete tooth-block or sectioned parts of the tooth. A mandibular incisor was embedded in acrylic resin in the muffle mould (B).

A **B**

Figure 2 The bottom of the mould was milled and it was fixed to the microscope table with putty.

The bottom of the mould was milled after which it was fixed on the microscope table with putty (fig.: 2). Each tooth-block was sectioned 5 mm from the root apex. After the apical canal had been irrigated with 2% NaOCl, the sectioned surface of the apical root with the apical root canal was photographed using a microscope with digital camera (Photomakroskop M400 microscope, Wild, Heerbrugg, Switzerland) at ×40 magnification. It was confirmed that the canal outline was clearly visible. The tooth was then remounted in the mould and root canal instrumentation was performed. After instrumentation, the mould was opened and the sectioned surface was photographed again. These images were then saved as Tagged Image File Format (TIFF) images. Using a KS100 Imaging system 3.0 (Carl Zeiss Vision GmbH, Hallbergmoos, Germany), the two images of the sectioned surface of the apical root before and after instrumentation were superimposed on one another. The second canal outline (after instrumentation) was compared to the first canal outline (before instrumentation). If the first outline was not in contact with the second one at any point along the circumference, it was deemed that the inner layer of dentine had been removed from the entire canal wall (=100%). If the second outline was in contact with the first outline in one or more places, indicating that the inner layer had not been removed from that part of the canal wall, the length of both the contact portion and the noncontact portion was measured (figs.: 3 and 4).



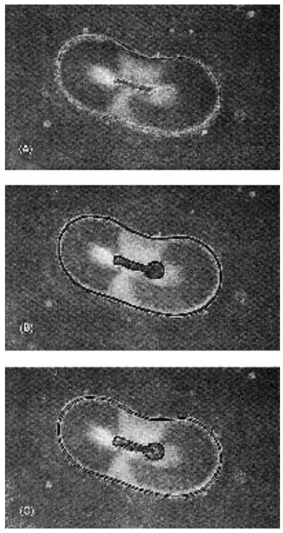


Figure 3 (left) Two images of a sample from the circumferential filing group. (A) The image before instrumentation. The outlines of the root and the canal were both drawn in blue. The canal perimeter was 2.49 mm. (B) The image after instrumentation. The outlines of the root and the canal were both drawn in red. (C) The outlines in (A) were superimposed on the outlines in (B). The two root outlines (blue and red) were completely superimposed while the two canal outlines were partly superimposed. The inner layer of dentine had been removed from 65.9% of the canal wall.

Figure 4 (right) Two images of a sample from the balanced force group. (A) The image before instrumentation. The outlines of the root and the canal were both drawn in blue. The canal perimeter was 2.90 mm. (B) The image after instrumentation. The outlines of the root and the canal were both drawn in red. (C) The outlines in (A) were superimposed on the outlines in (B). The two root outlines (blue and red) were completely superimposed, while the two canal outlines were partly superimposed. A round preparation (red) was created at the right end of the long oval canal, leaving 67.2% of the canal wall unprepared.

The canal perimeter and the length of the arc where the inner layer of dentine had been removed were also measured. The percentage of this arc was calculated (<100%). One investigator measured all specimens without knowing which instrumentation technique had been performed.

Before the second photograph was taken, the canals were instrumented using two different techniques. In all the teeth a so-called lingual conventional access cavity (Mannan et al. 2001) was made. The working length was established by deducting 1 mm from the actual canal length, which had been previously determined by inserting a size 15 file into the canal until the tip of the file was just visible at the apical foramen. The coronal part of each canal was preflared using Gates–Glidden drills (Dentsply Maillefer, Ballaigues, Switzerland), sizes 50 and 70 (sizes 1 and 2) to a depth of 7 mm short of the working length, and ISO size 90 (size 3) to a depth of 8 mm short of the working length. Regardless of which technique was used, each canal was irrigated between each instrument with 2 mL of a freshly prepared 2% solution of NaOCl, using a syringe and a 27-gauge needle. After completion of the preparation, the canal was irrigated with 10 mL of 2% NaOCl.

Balanced force technique

Each canal was instrumented with Flexofiles (Dentsply Maillefer) using the balanced force technique (Roane et al. 1985). Briefly, a size-10 file was introduced into the canal until binding, and rotated 90 to 180 degrees clockwise with light apical pressure.

Next, the file was rotated in a counterclockwise direction 120 to 360 degrees at an inward apical pressure that was light for small files (≤size 25) and heavier for large files (>size 25). Debris was removed by means of a slight outward pull with clockwise rotations. Such preparation was continued until the working length – 1 mm short of the apex – was reached. The same procedures were followed for all the subsequent instruments, sizes 15–40, finishing with a size-40 master apical file.

Circumferential filing technique

Each canal was prepared using Flexofiles (Dentsply Maillefer) and a size 10 was inserted up to the working length, i.e., 1 mm short of the apex, using circumferential filing, until the file was loose. Sizes 15–40 were then taken to the working length in sequence, ending with a size-40 master apical file. Each file was moved around the long oval canal at least twice until the file was loose.

The differences between the two groups with respect to canal perimeter and the percentage of the arc where the inner layer of dentine had been removed were analysed using a Mann–Whitney U-test. The level of significance in the test was set at $P < 0.05$.

Results

The results are shown in Table 1. There was no significant difference in canal perimeter between the two groups ($p=0.576$), confirming that both were balanced in respect of anatomy. The circumferential filing technique removed the inner layer of dentine from a greater proportion of the perimeter of the canal wall than the balanced force technique (Table 1; Figs 3 and 4). However, the difference was not statistically significant
($p =0.101$).

Discussion

Most rotary instrumentation produce a round preparation (Hülsmann et al. 2001, Wu & Wesselink 2001). When the balanced force technique was performed in oval canals, the round preparation did not include the recesses, with the result that a portion of the canal wall was unprepared (Wu & Wesselink 2001). In this study, the balanced force technique again prepared less than 40% of the canal wall (Fig. 4; Table 1). The use of larger files in order to scrape more canal walls is not to be recommended, because these unnecessarily weaken the mesial and/or distal walls.

The concept behind circumferential filing is that a small file can move around the oval canal on the outstroke. Thus, it was speculated that the file could contact the whole canal wall without the risk of mesial or distal perforation. In this study, a size 90 Gates–Glidden drill had been used to 8 mm from the apex to facilitate the action of circumferential filing in deeper root canals and the circumferential filing did indeed prepare more aspects of the wall than the balanced force technique (Table 1). However, 40% of canal wall was not instrumented even after the use of circumferential filing. There is no evidence to prove that using a technique to remove dentine from 60% of the canal wall will lead to a higher success rate than using a technique that removes dentine from 40% only.

In the study by Reynolds et al. (1987), circumferential filing scraped 29, 60 and 64% of the wall in the apical, middle and coronal portions of root canals, respectively. It is unclear why this technique scraped more aspects of the wall in the middle and coronal portions than in the apical portion. The results of this study are in line with those of others (Reynolds et al. 1987, Zuolo et al. 1992, Siqueira Jr et al. 1997, Evans et al. 2001), demonstrating that thus far no technique has proved capable of scraping the whole circumference of the wall.

In this study, no stepback procedure was performed. Clinically, larger files are used during the stepback, but large files cannot prepare the narrow recesses in oval canals. However, including stepback may widen the canals in both groups and increase the percentage of prepared wall.

The capability of instrumentation to remove the inner layer of dentine was evaluated using only one section in this study. In cross-section the shape of root canals is not always oval at each level within a root (Wu et al. 2000b). Because the presence of oval canal was confirmed at the level 5 mm from the apex in this study, evaluation at the same level guaranteed observation of the effect of instrumentation in oval canals, which was the purpose of this study.

In this study, regardless of which technique was used, the instruments did not succeed in contacting 40% or more of the root canal wall. As yet, no technique has proved capable of removing dentine from the entire wall. This indicates that it is not possible to remove the inner layer of dentine from the entire canal wall of oval canals. Nevertheless, clinically high success rates have been recorded, even in the absence of strong disinfectants designed to kill microorganisms in the dentinal tubules (Peters et al. 1995).

The hypothesis that the mechanical removal of heavily infected dentine is vital to the success of the treatment is being challenged. Therefore, it is not advisable to enlarge canals unnecessarily by means of large-sized instruments; rather the canals should be widened to allow effective irrigation and filling.

Table 1 The capability to remove the inner layer of dentine at a level 5 mm from the apex

Techniques	Mean and SD of canal perimeter (mm)	Mean and SD of the percentage of the arc from which the inner layer was removed (%)
Balanced force	2.11 ± 0.84	38.6 ± 17.5
Circumferential filing	2.18 ± 0.62	57.7 ± 29.4

3

Comparison of mandibular premolars and canines with respect to their resistance to vertical root fracture

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M.K. Wu, L.W.M. van der Sluis, P.R. Wesselink.

Abstract

Aim To compare the force required to vertically fracture uninstrumented and instrumented mandibular premolars and canines.

Methodology Two groups of single round-canal mandibular premolars and two groups of single oval-canal mandibular premolars were selected after radiographs indicated an internal long:short diameter of 1 or > 2 at a level 5 mm from the apex. In addition, two groups of maxillary and mandibular canines were selected. The root canals of three of these groups (one from each category) were conventionally enlarged using same-sized instruments, while the other three groups were uninstrumented. Each root was mounted in an acrylic resin cylinder, and the force required to cause vertical root fracture (VRF) was measured using an Instron tester.

Results No significant difference in resistance to VRF was found between the round- and oval-canal premolars with ($p=0.9$) or without ($p=0.6$) instrumentation. The average force required to fracture the uninstrumented premolars and canines was 698 and 566 N, respectively. The average force required to fracture the instrumented premolars and canines was 490 and 554 N, respectively. The force required to fracture the instrumented premolars and canines was 30% ($p<0.05$) and 2% ($p=0.9$) lower, respectively, than that required to fracture their uninstrumented counterparts.

Conclusion The instrumented mandibular premolars have a higher risk to fracture than the uninstrumented mandibular premolars.

Introduction

Vertical root fracture (VRF) occasionally occurs in endodontically treated teeth. The prevalence of VRF is not equally distributed over the different tooth types (Testori et al. 1993, Tamse et al. 1999). Maxillary and mandibular premolars have both recorded a high prevalence (Tamse et al. 1999). It is important to establish which procedures in the endodontic therapy may increase the risk of VRF.

It is generally accepted that the removal of excessive amounts of radicular dentin compromises the root, and that the amount of dentin remaining is directly related to the strength of the root (Gutmann 1992, Trope & Ray 1992, Pilo et al. 1998, Lerchirakan et al. 2002). In addition, a high concentration of NaOCl solution has been found to weaken dentin, (Sim et al. 2001) as has the long time exposure to calcium hydroxide (Andreasen et al. 2002).

Some 25% of the roots have a long, oval-canal, while the other 75% have a relatively round-canal (Wu et al. 2000). The preparation in oval-canals does not usually include the buccal and lingual recesses (Wu & Wesselink 2001). Therefore, dentin is only removed from the mesial and distal canal walls. In round-canals, however, dentin is removed in all directions. It may be that more dentin is removed from round-canal roots than from oval-canal roots. Whether round-canal roots or oval-canal roots are more weakened by instrumentation is unknown.

The purpose of this in vitro study was to measure the force required to vertically fracture the roots of round- and oval-canal mandibular premolars, and maxillary and mandibular canines.

Materials and methods

Two hundred mandibular premolars from a pool of extracted human permanent teeth stored in 5% formol-saline were mesio-distally and bucco-lingually radiographed. All radiographs were taken using a dental X-ray generator, which was set at 50 kV and 9 mA. Twenty-nine mandibular premolars with a single round-canal were selected after radiographs indicated an internal long:short diameter of 1 at a level 5 mm from the apex. Twenty-three mandibular premolars with a single oval-canal were selected after radiographs indicated an internal long:short diameter of >2 at a level 5 mm from the apex (Wu et al. 2000). In addition, 24 maxillary and mandibular canines were selected and mesio-distally and bucco-lingually radiographed. It has been found that 95% of both maxillary and mandibular canines have a relatively round-canal (Wu et al. 2000).

A total of 14 premolars with a round-canal, 11 premolars with an oval-canal, and 11 canines were instrumented. The remaining teeth were not instrumented. Care was taken that the radiographic canal diameter was similar between the two groups, confirming that in each pair the two groups were balanced by anatomy.

The coronal part of each tooth was removed using an Isomet 11-1180 low-speed saw (Buehler Ltd, Evanston, IL, USA) with copious water coolant, leaving roots 14 mm in length. To exclude the presence of dentine cracks, the roots were examined under a Photomakroskop M400 microscope (Wild Heerbrugg, Switzerland) at ×40 magnification. No dentine crack was observed. The working length for the canal instrumentation was 13 mm. The patency of each canal was confirmed by inserting a size 20 file through the apical foramen before and after completion of the root canal preparation. The coronal 7 mm of each canal was preflared using Gates Glidden drills

(Dentsply Maillefer, Ballaigues, Switzerland), ISO size 50, 70 and 90 (sizes 1, 2 and 3).

All canals were prepared with K-files (Dentsply Maillefer) using circumferential filing. Sizes 15–50 were taken to the full working length. The canal was then flared up to size 80 using a step-back technique at 1 mm increments, resulting in a taper of 0.10 mm mm^{-1}. Between, each instrumentation the canals were irrigated with 2 ml of a freshly prepared 2% solution of sodium hypochlorite, using a syringe and a 27-gauge needle. After the completion of hand instrumentation, each canal was flushed with 5 ml of 2% NaOCl.

In order to obtain a standardized cylindrical coronal orifice, the coronal 2 mm of each canal (including those in which no canal instrumentation was performed) was enlarged to 1.5 mm diameter using a Gates Glidden drill size 6. The specimens, of which the canal orifice was larger than 1.5 mm before the orifice preparation, were discarded.

All specimens were stored in water until measuring the force required to cause VRF using an Instron tester. Here the application of a vertical loading force until fracture was similar to the technique used in the studies by Sedgley and Messer (1992) and by Apicella et al. (1999). The apical 5 mm of each root was mounted in an acrylic resin cylinder 20 mm in height. A steel ball 5 mm in diameter was placed directly over the prepared cylindrical coronal orifice. An Instron test machine (Instron 6022 tester, Instron, Canton, MA, USA) then applied a slowly increasing force on the steel ball, at a rate of 1.0 mm per min, until the occurrence of VRF.

Because the steel ball contacted the entire circumference of the prepared canal orifice, the force applied on the root was equally distributed in all directions. The force required to fracture the root was recorded in Newtons.

A Mann–Whitney *U* tests was used to analyse the difference between the instrumented and uninstrumented teeth with respect to the force required to fracture the root; the level of significance was set at $p<0.05$.

Results

Since no significant difference was found in the force required to fracture roots between the round-canal and oval-canal premolars, either with ($p=0.9$) or without ($p=0.6$) the instrumentation, the data of all instrumented premolars were pooled, as were the data of all uninstrumented premolars. The forces required to cause VRF are shown in Table 1. The force required to fracture the instrumented mandibular premolars and canines was lower by 30% ($p<0.05$) and 2% ($p=0.9$), respectively, than that required to fracture the uninstrumented mandibular premolars and canines.

Discussion

During chewing the occlusal load on mandibular premolars is three times as high as the load on canines (Shinogaya et al. 1999). The resistance of uninstrumented mandibular premolar roots to VRF was 698 N in this study, noticeably higher than the resistance of canine roots (566 N). However, the force required to fracture the instrumented mandibular premolar roots was 30% lower ($p<0.05$), whereas the weakening of canine roots by instrumentation was negligible ($p=0.9$). Clinically, maxillary and mandibular premolars have recorded a much higher prevalence of VRF than maxillary and mandibular canines, 56 versus 8% (Tamse et al. 1999).

Actually, the average load of approximately 100 N applied on mandibular premolars (Shinogaya et al. 1999). was much lower than the average force required to fracture the instrumented mandibular premolar roots (490 N). Only when a very high load is applied on an extremely weakened mandibular premolar, VRF may take place.

In morphology studies, the canal diameter of the single-canal mandibular premolars was similar to that of the canines (Kerekes & Tronstad 1977). This is the reason that, when common-taper instruments (2% tapered) are used, sizes 50–70 are recommended as the master file for both single-canal mandibular premolars and maxillary and mandibular canines (Tronstad 1991). In the present study, a size-50 master file was used. It is unknown why those mandibular premolars, which were enlarged to the same size canal as the canines, were weaker and more prone to fracture. Great Taper instruments have recently been introduced, and the sizes GT 20–10 and GT 20–12 have been recommended for single-canal mandibular premolars (Buchanon 2001). The apical and coronal enlargement performed in this study is comparable to the enlargement using GT instruments as suggested by Buchanan (Buchanon 2001) in Table 2. Our data suggest that all these enlargements may significantly weaken mandibular premolars. Rosen and Partida-Rivera (1986) found in an in vitro study that the smaller the mesio-distal diameter of the root, the greater the incidence of fracture. Thus, the significant weakening of mandibular premolars may be explained by their relatively small mesio-distal root diameter (Wu et al. 2000).

In this study, the coronal part of each tooth was removed using a saw. It could not be excluded that the sawing procedure might cause a potential damage in the root. However, when sufficient cooling was applied, occurrence of crack caused by the sawing procedure was rarely reported (Wu et al. 2000, Wu & Wesselink 2001, Kerekes & Tronstad 1977).

It is considered desirable to remove the inner layer of dentine from all aspects of the root canal wall during root canal treatment, (Walton & Torabinejad 1996) and for this reason large-sized instruments are usually recommended (Tronstad 1991). However, it has been found impossible to remove the inner layer of dentine from the entire canal wall, no matter which instrumentation technique was used (Reynolds et al. 1987, Zuolo et al. 1992, Siqueira et al. 1997, Evans & Speight 2001, Wu et al. 2003) and that clinically high success rates have been recorded even in the absence of strong disinfectants designed to kill microorganisms in the dentinal tubules (Peters et al. 2001). Thus far, there is no evidence indicating that it is necessary to scrape the entire canal wall. Probably, the canals need to be opened up to a minimum size, that allows effective root canal irrigation and obturation, while over enlargement should be avoided to prevent unnecessarily weakening of the roots.

In this study, around 30% of the root fracture resistance was lost after instrumentation in mandibular premolars (Table 1). Similar results have been reported for different tooth types by Trope and Ray (1992) and Lertchirakarn *et al.* (2002). Thus, it appears that it may be necessary to reduce the extent of root canal enlargement and develop new root filling materials that can strengthen the root (Trope and Ray 1992).

The strength and hardness of vital dentine may differ from that of non-vital dentine (Walton et al. 1984).Teeth, which have similar dentine, should be used in both instrumented and uninstrumented groups. Two hundred mandibular premolars and 24 canines were needed in this study, and it was difficult to find so many teeth with a vital pulp or so many teeth with a necrotic pulp. In this study, formalin-stored teeth were used. It is not clear, however, whether all formalin-stored teeth had comparable dentine.

On the basis of the results, we conclude that the commonly instrumented mandibular premolars have a higher risk to fracture than the uninstrumented mandibular premolars. However, canines are not significantly weakened by common instrumentation.

Acknowledgements

The authors wish to thank Drs R. Cohen and Y. Jalili for the laboratory work.

Table 1 Force required to cause vertical root fracture.

Tooth group	Root canal instrumentation	N	Force (in Newton) required to cause vertical root fracture	
			Mean ± SD	Significance[a]
Mandibular premolar ($N = 52$)	No	27	698 ± 298	$p < 0.05$
	Yes	25	490 ± 135	
Canine ($N = 24$)	No	13	566 ± 208	$p = 0.9$
	Yes	11	554 ± 232	

[a] Comparison of the difference between the instrumented and uninstrumented teeth with respect to the force required to cause vertical root fracture.

Table 2 Apical and coronal enlargement performed in this study and suggested by Buchanan (2001).

	Instruments	Enlargement at 5 mm from the apex (mm)	Coronal enlargement (mm)
In this study	K-files #15-80, Gates Glidden #1-3	0.8	0.9
Suggested by Buchanan	GT 20-10	0.7	1.0
	GT 20-12	0.8	1.0

4

An evaluation of the quality of root fillings in mandibular incisors and maxillary and mandibular canines using different methodologies

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Abstract

Aim To evaluate the quality of root fillings in mandibular incisors and maxillary and mandibular canines using different methodologies of evaluation, namely radiographs, the fluid transport test and the percentage of gutta-percha (PGP), and to determine if a correlation occurs between the results of the different methodologies used.
Methodology One group of mandibular incisors with oval canals (n=20) and one group of maxillary and mandibular canines (n=20) were instrumented and obturated by cold lateral compaction using AH 26 as the sealer. The filled roots were bucco-lingually and mesio-distally radiographed. Using a scoring system, the quality of each root filling was radiographically evaluated, the higher the score the poorer the quality. Fluid transport along the root filling was then measured using a fluid transportation device. Each root was horizontally sectioned 4 and 6 mm from the apex. Images of the cross-sections were taken, using a microscope and a digital camera. Images were scanned into a PC as TIFF images. Using a KS 100 Imaging system the canal area and the gutta-percha filled areas were measured. The percentage of gutta-percha filled areas was calculated.
Results Considering the radiographic scores of the two different projections together the score was significantly higher for the mandibular incisors than for the canines (p=0.039). The radiographic score was significantly higher for the mesio-distal radiograph in comparison with the bucco-lingual radiograph (p=0.0001), for the canines as well as the incisors. Using only the bucco-lingual radiograph there was no significant difference between the mandibular incisors and the canines (p=0.992). The mandibular incisors displayed significantly more fluid transport than the canines (p=0.049). A significantly greater percentage of gutta-percha filled areas was found in the cross-sections of canines as compared to the cross-sections of mandibular incisors (p=0.000001). The correlation between the radiographic score of the mesio-distal radiograph and the PGP 4 and 6 mm was significant (p=0.013). There was no significant correlation between the FT and the radiograph or the FT and the PGP.
Conclusions The quality of the root fillings in oval canal-mandibular incisors may be compromised.

Introduction

Long oval canals are a common appearance in the apical 5 mm in human teeth (Wu et al. 2000). In some tooth groups the occurrence of a long oval canal (a canal with a bucco-lingual diameter>two times the mesio-distal diameter) was even more than 50%. Common instrumentation techniques leave uninstrumented wings in the canal where debris can remain (Goodman et al. 1985, Hülsmann et al. 2001, Wu & Wesselink 2001, Wu et al. 2003). When debris is present in the wings it is impossible to fill these areas (Wu & Wesselink 2001).

Using the cold lateral compaction technique it may be difficult to fill the wings of the oval canal because the secondary cones do not always reach these recesses. These uninstrumented and unfilled wings can create problems because they may contain bacteria which can grow when they receive nutrients from the periapical region or lateral canals (Dahlen & Moller 1992). When these unfilled recesses are through and through, from the coronal to apical, bacterial elements and nutrients for bacteria can migrate from the coronal to the apical region (Torabinejad et al.1990).

In order to judge the quality of an endodontic treatment, the radiograph is used. When on the radiograph a tooth is seen with a not homogenous filled canal space combined with a periapical lesion or clinical symptoms it is easily decided to revise the treatment. However, when it is concluded on the radiographic image that the root filling looks well condensed, the assumption is that the root canal treatment has been performed correctly so no retreatment seems indicated. In vitro studies have shown that the mesio-distal radiograph reveals more inadequacies in the root filling than the bucco-lingual radiograph (Kersten et al. 1986, Kersten et al. 1987, Dummer et al. 1993, Dummer et al. 1994). It has been concluded that the clinically taken radiograph is not reliable to judge the quality of the root canal filling (Kersten et al. 1986, Kersten et al. 1987, Dummer et al. 1993, Dummer et al. 1994). In the oval canal, this aspect can be more prominent than in the round canal because the difference between the bucco-lingual diameter and the mesio-distal diameter is much larger.

In many studies the percentage of gutta-percha filled area (PGP) has been measured (Kersten et al. 1986, Eguchi et al. 1985, Beer et al. 1987, Silver et al. 1999). In general, the higher the PGP, the smaller the area of sealer and voids, the better the quality of the root canal filling (Wu & Wesselink 2001, Kontakiotis et al. 1997). The PGP score may reveal filling problems in the oval canal. When the wings are occupied by debris, the PGP score will be lower than in round canals. Because the shape of the wings is irregular, it may be difficult to place secondary cones into the wings when the root canal is filled using the cold lateral compaction technique, so here too the PGP score may be lower than in the round canals.

Leakage tests have been performed for a long time in endodontic studies (Wu & Wesselink 1993). The most used technique was, and still is, the dye penetration. This technique, however, is a passive leakage test and has some drawbacks. The penetration of the dye can be stopped by entrapped air or the dye can loose its color when it is in contact with some filling materials or strong acidic solutions used to decalcify the tooth (Wu et al. 1994, Wu et al. 1998, Swanson & Madison 1987, Vassiliadis et al. 1996) and it gives no information of the volume of fluid leaking along the root fillings. The fluid transportation model has been designed to overcome these problems (Wu & Wesselink 1993, Derkson et al. 1986). In the fluid transportation model the root canal fillings to be measured are placed under a constant air pressure starting at the coronal part of the root canal. The apical part of the root canal is attached to a pipette filled with water and an air bubble. If there is a void in the root canal filling running from the coronal to the apical the air bubble in the pipette will move in outward direction because of the air pressure. This way voids in the canal filling can be detected going through and through from the coronal part to the apical part even if these voids are very small. With this model also the volume of fluid transport can be quantified whereas this is not possible with dye leakage

Some studies have combined radiographs, dye penetration and PGP to determine the quality of a root canal filling (Kersten et al. 1987) whereas other studies used radiographs and dye penetration (Dummer et al. 1993, Dummer et al. 1994, Beyer-Olsen et al. 1983). In the studies of Beyer-Olsen et al. (1983) and Kersten et al. (1987), the correlation between the different tests was evaluated. Kersten et al. (1986) showed limited correlation between the bucco-lingual radiograph and the mesio-distal radiograph, the dye penetration and the stereomicroscopic evaluation. In the Beyer-Olsen et al. (1983) study, a small correlation was found between the radiograph and the dye leakage in some groups. In both studies dye leakage was used, which is not a reliable method to detect voids in the canal filling and for that reason it was decided to re-examine this problem.

The purpose of this study was to evaluate the quality of the canal filling of mandibular incisors compared with that of mandibular and maxillary canines using three different techniques of evaluation: (1) radiographs made in bucco-lingual and mesio-distal directions (2) the volume of fluid transported using the fluid transportation model and (3) the amount of gutta-percha present in the canal (PGP) at two levels (4 and 6 mm from the apex). Also the correlation between the outcomes of different evaluation methods was evaluated.

Materials and methods

Specimen selection and preparation

From a pool of extracted human permanent teeth stored in 5% formol—saline 20 mandibular incisors were selected after mesio-distal radiographs indicated a bucco-lingual internal diameter of more than 0.6 mm at 5 mm from the apex (Wu et al. 2000). These teeth were selected because the single canal mandibular incisor has an oval shaped canal. Twenty maxillary and mandibular canines were selected, they have a more round shaped canal (Wu et al. 2000). In all teeth, a lingual conventional access cavity (Mannon et al. 2001) was made. Root canal instrumentation and obturation were executed by the same operator. The working length (WL) was established by deducting 1 mm from the actual canal length, which has been previously determined by inserting a size 15 file (Dentsply/Maillefer,Ballaiques,Switzerland) into the canal until the tip of the file was just visible at the apical foramen. The coronal part of each canal was preflared, using Gates Glidden drills (Dentsply/Maillefer) ISO 70 (size: 2) for the incisors and ISO 90 (size: 3) for the canines to a depth 6 mm short of the WL. All canals were prepared using K files (Dentsply/Maillefer) according to the circumferential filing technique. The master apical file (MAF) for the incisors was file size 40 and for the canines size 50. The step-back preparation for the incisors was performed with file sizes 45, 50 and 55 to 1, 2 and 3 mm, respectively, from WL and for the canines 55, 60 and 65 to 1, 2 and 3 mm, respectively, from WL. Pressure was applied to the shank of the file towards the canal walls in all directions during outward stroking of the instruments. Each canal was irrigated with 2 mL of a freshly prepared 2.5% solution of NaOCL between each instrument, using a syringe and a 27—gauge needle. After the preparation had been finished, the canal was dried with paper points (Dentsply/Maillefer), and filled by cold lateral compaction of gutta-percha using AH Plus (Dentsply, Konstanz, Germany) as sealer. Finger spreader B (Dentsply/Maillefer), and accessory cones number 25 were used. When the spreader was used the first time it was placed not more than 1 mm shorter than working length.

Radiographic assessment

After filling the canals, radiographs were taken in a bucco-lingual and mesio-distal direction. All radiographs were taken using a dental X-ray generator, *x* range 50/1 (Castellini, s.p.a.) which was set at 50 kV and 9 mA, and the films (Kodak Ultraspeed speed D) were exposed for 0.5 s with a source object distance of 35 mm. The films were manually developed, using developer for 15 s, water, and fixer for more than 60 s. Hereafter, films were rinsed with water, dipped in alcohol and air-dried. The radiographs were examined randomly by three examiners working independently. The examiners were trained and calibrated. The quality of the root canal filling was scored on a four point scale, the higher the score the poorer the quality (Kersten et al. 1987).

1. Well-condensed gutta-percha which filled the entire prepared root canal, was well adapted to the canal wall and showed only a few, minor air bubbles (less than 0.25 mm in diameter) or separate gutta-percha cones only at the cervical level.
2. An imperfectly condensed filling that might be a little short (0.5 mm or less), and that might show irregularities of less than 1 mm in the adaptation.
3. Inadequately, condensed gutta-percha with irregularities of less than 2 mm, a filling that might be 1.5 mm short and/or might show separate gutta-percha cones in the coronal half of the root canal.
4. Poorly condensed gutta-percha with irregularities of more than 2 mm, a filling that might be more than 2 mm short and/or might show separate gutta-percha cones in the apical half of the root canal.

Fluid transport (FT).

After the radiographic assessment the roots were then stored at 100% humidity and 37 °C for 2 weeks. Thereafter, the root portion of each tooth was embedded in an acrylic resin cylinder. The margins adjoining the acrylic resin and tooth were sealed with cyanoacrylate (Permacol, dispenser PX-10, Ede, Holland). Each root was mounted in the FT device described previously by Wu&Wesselink (1993). All connections were closed tightly by twisting pieces of stainless steel wire in a water bath at 20 °C. FT along the root filling was measured under a head space pressure of 30 kPa (0.3 atm.) during a 24-h period. The results after calculation were expressed as $\mu L\ h^{-1}$.

Cross-section of root filling

Using a low-speed saw (Sagemicrotom 1600; Leitz, Wetzlar, Germany) all roots were horizontally sectioned 4 and 6 mm from the apex. The specimen was pushed towards the rotating saw disc using light pressure with constant fresh cooling water bathing the teeth. Previous studies indicate that under these conditions no smearing of gutta-percha is detected at a magnification×50.(Wu & Wesselink 2001). Using a digital camera pictures of the sections were taken under a Photomacroscoop M400 microscope (Wild, Heerbrugg, Switzerland) at ×40 magnification. These photographs were then scanned as Tagged Image File Format (TIFF) images. Using a KS 100 Imaging system 3.0 (Carl Zeiss Vision GmbH, Hallbergmoos, Germany) the area of the canal and gutta-percha were outlined by hand and then measured. The percentage of gutta-percha filled area (PGP) was calculated. The data for the radiographic evaluation, the fluid transportation and PGP were analyzed statistically using the Mann–Whitney *U*-test, the Spearman test was used to examine the correlation. The level of significance was set at $p<0.05$.

Results

The results of the different evaluations are shown in Table 1. Considering the radiographic scores of the two different projections together the score was significantly higher for the mandibular incisors than for the canines ($p=0.039$). The radiographic score was significantly higher for the mesio-distal radiograph compared to that of the bucco-lingual radiograph ($p=0.0001$), both the canines and the incisors. Using only the bucco-lingual radiograph, there was no significant difference between the mandibular incisors and the canines ($p=0.992$). Using only the mesio-distal radiograph the canines seemed significantly better filled ($p=0.003$). In the mandibular incisor group, the difference of the radiographic scores between the mesio-distal and the bucco-lingual projection was larger than in the canines ($p=0.039$). The mandibular incisors displayed significantly more fluid transport than the canines ($p=0.049$). A significantly higher percentage of PGP was found in the cross-sections of canines than mandibular incisors ($p=0.000001$). The correlation between the radiographic score of the mesio-distal radiograph and the PGP at 4 and 6 mm was significant ($p=0.013$), the correlation coefficient is 0.389. No correlation was found between the results of the FT and the radiographic scores or the FT and the PGP.

Discussion

The poorer results of the root fillings in oval canal incisors could be explained because it is not possible to completely instrument the entire oval canal with use of the balanced force technique (Wu et al. 2003). Using this rotation technique to prepare the canal leaves large portions of the canal wall uninstrumented. If the canal wall and the recesses are not clean it is not possible to fill the canal completely. Also other methods of cleaning and shaping, including mechanical rotary preparation, have not resulted in a clean oval canal (Hülsmann et al. 2001, Siqueira et al. 1997, Weiger et al. 2002, Rodig et al. 2002), and probably will result in incomplete root canal fillings no matter which gutta-percha technique is used.

The significant correlation between the PGP (4 and 6 mm) and the quality diagnosed from the mesio-distal radiograph can be explained by the fact that the mesio-distal radiograph gives a more reliable image of the quality of the root canal filling than the clinically taken bucco-lingual radiograph (Kersten et al. 1986, Kersten et al. 1987, Dummer et al. 1993, Dummer et al. 1994). If the PGP is low, the volume of voids in the root canal filling will be larger so the quality of the root canal filling on the mesial–distal radiograph will be worse. In the bucco-lingual radiograph these voids may be masked by superimposition of filling material. Our results suggest that, although the clinically taken bucco-lingual radiograph is not reliable to judge the quality (Kersten et al. 1986, Kersten et al. 1987, Dummer et al. 1993, Dummer et al. 1994), the mesio-distal radiograph may provide reliable information about the quality of the root filling.

There was no correlation between the FT and the radiograph or the FT and the PGP because the FT model only shows leakage when there is at least one void extending from the coronal to the apical. A root canal filling which looks badly condensed on the radiograph can contain many cul-de-sac- type voids and no FT will occur. The same counts for the PGP. The PGP may give a poor image of the root canal filling at the level of the section, but the void detected may be of the cul de sac type and not run from the coronal to the apical therefore not showing FT. On the other hand, very small voids through and through, invisible on radiographs or in cross-sections, may be detected by the FT test. To evaluate if a root filling material or technique has the capacity to completely fill the root canal, the mesio-distal radiograph and/or the PGP can give a good impression. The additional use of the FT model can show us additional through and through voids which cannot be detected by the other methods.

This study confirms the conclusion of other studies (Kersten et al. 1986, Kersten et al. 1987, Dummer et al. 1993, Dummer et al. 1994) that the reliability of the clinically taken bucco-lingual radiograph of oval and round canals does not give a reliable presentation of the quality of the root canal filling. This reliability is even less for the oval canals than for the round canals. The only reliable information the clinically taken radiograph can give is the length of the root canal filling (Eckerbom & Magnusson 1997).

In this study, two cross-sections were made at 4 and 6 mm, to compare the quality of compaction of the root filling between oval and round canals, because these areas are representative. The apical part of the root canal will be round in most cases and the coronal part of the root canal is prepared with the gates-glidden drills and for this reason not interesting for the comparison between the round and oval shape of the root canal.

The canines were prepared to MF 50 and the incisors till MF 40. This indicates that the diameter of the round canals is larger than the oval canals. It is not known if this has an influence on the filling quality.

In the evaluation of the root filling quality, the length of the root filling was also evaluated. Because the root canals were not over- or under filled in this study the length of the root fillings did not influence the data.

Conclusion

With the results of three different evaluations in this in vitro study we conclude that the quality of root canal fillings in long oval canals may be compromised.

Table 1 Multiple evaluations of the quality of root fillings in mandibular incisors and maxillary and mandibular canines.

Tooth type	**Bucco-lingual radiographic score (Mean±SD)**	**Mesio-distal radiographic score (Mean±SD)**	**Combined mesio-distal and bucco-lingual score (Mean±SD)**	**Percentage of gutta-percha-filled area in % at 4 and 6 mm from apex (Mean±SD)**	**Fluid transport along root fillings in μL h^{-1} (Mean±SD)**
Mand. Inc. (*n*=20)	1.36±0.64	2.56±0.79	1.96±0.93	58.0±10.5	1.00±1.20
Canine (*n*=20)	1.36±0.58	2.08±0.85	1.72±0.81	71.1±11.5	0.25±0.50
Significance	p=0.992*	p=0.003*	p=0.039*	p=0.00001*	p=0.049**

*Using a *t*-test; **using a Mann–Whitney *U*-test.

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An evaluation of the influence of passive ultrasonic irrigation on the seal of root canal fillings

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Abstract

Aim To evaluate the influence of passive ultrasonic irrigation on the seal of root canal fillings

Methodology Forty mandibular premolars were distributed equally into two groups and the root canals cleaned and shaped; they were than filled with gutta-percha and AH26 using the warm vertical compaction technique with the System B device. In one group passive ultrasonic irrigation (PUI) was applied, after completion of instrumentation and hand irrigation. In the other group PUI was not applied. Thereafter leakage of glucose was evaluated by measuring its concentration once a week for a total period of 56 days using a glucose penetration model. Differences between the groups in terms of glucose concentrations were statistically analyzed with the Mann-Whitney test; the level of significance was set at p=0.05.

Results After the first month the root fillings in teeth where PUI had been used, sealed the root canal significantly better than in teeth where no PUI had been used (p=0.017).

Conclusion Root fillings sealed the root canal better when passive ultrasonic irrigation (PUI) had been used.

Introduction

During passive ultrasonic irrigation (PUI) a small ultrasonically oscillating file or smooth wire (e.g. size15) is placed in the centre of the root canal following canal shaping, (Ahmad et al. 1987a). Because the root canal has been enlarged, the irrigant can flow in the root canal and the file or wire can vibrate relatively freely, which will result in more powerful acoustic streaming (Ahmad et al. 1987a). Passive ultrasonic irrigation (PUI) with sodium hypochlorite (NaOCl) as the irrigant, removes more dentine debris, planktonic bacteria and pulp tissue from the root canal than syringe irrigation (Huque et al. 1998, Lee et al. 2004a, Gutarts et al. 2005). During PUI more dentine debris can be removed from the isthmus, oval extensions in the root canal and irregularities from the root canal wall (Goodman et al. 1985, Lee et al. 2004a).

It is generally accepted that relatively few dentists use PUI. Remaining dentine debris, which can not be removed during hand irrigation, will be packed into oval extensions and irregularities of the root canal (Wu&Wesselink 2001). If oval extensions are filled with dentine debris the filling material can not adapt to the canal wall and leakage may ensue (Wu & Wesselink 2001, van der Sluis et al. 2005a) because the filling material and sealer are not compacted against a clean root canal wall but against dentine debris particles no matter which root filling technique or materials are used.

It is unclear whether root fillings, placed after PUI, seal the root canal better because more dentine debris is removed from the root canal. In the study of Wu et al. (2001) the quality of root fillings in oval canals was evaluated using the percentage of gutta-percha in the root canal (PGP). The mean PGP was 86.6% varying from 47.1 – 100%. Many oval extensions were not prepared and became filled with dentine debris. PUI was not used for irrigation of the root canals. In another study, where a similar methodology was used, but with PUI, the mean PGP was 98. 9% and varied from 94. 5 – 100%. This indicated that PUI removed effectively dentine debris from the oval extensions and thus allowed the gutta-percha to fill more completely the root canal (Ardila et al. 2003).

Healing following root canal treatment is assured through effective infection control (Sjögren et al. 1990). However, it is not clear whether a better sealing root filling leads to less periapical inflammation. Yamauchi et al. (2006) demonstrated, in an animal experiment, that less periapical inflammation occurred when root fillings were protected against coronal leakage by application of an additional coronal plug of filling material. Because an additional coronal plug leads to less coronal leakage (Chailertvanitkul et al. 1997), these data indicate that less coronal leakage leads to less periapical inflammation.

Different leakage models are used to detect and measure leakage along root fillings (Wu et al. 1993). Leakage tests are improving and recently Xu et al. (2005) reported a new model that measures the leakage of glucose molecules. This model consists of a tube where a concentrated glucose solution is placed and connected to the test element, while the apical side of the specimen is dipped in water. Glucose which leaks through the root canal accumulates in the apical chamber and is measured using an enzymatic reaction with a spectrophotometer. Glucose has a low molecule weight, and may be used as an indication for toxins that might penetrate the canal.

The aim of this study was to evaluate the influence of passive ultrasonic irrigation on the seal of root fillings.

Materials and methods

Digital radiographs from bucco-lingual and mesial-distal directions were made of extracted mandibular premolars that had been stored in water with added NaOCl for no coronal to the working length, where the bucco-lingual diameter was more than twice as large as the mesio-distal diameter, were selected. The curvature of the roots was measured following Schneiders methodology (Schneider 1971). The 40 specimens were divided equally in two anatomically comparable groups taking into account the curvature and the oval shape of the root canals. Two teeth were used as negative controls (the roots were completely covered with nail varnish) and two as positive control (canals were filled using lateral compaction of gutta-percha cones without sealer).

The teeth were decoronated and all roots were reduced to a length of 12 mm. Working length (WL) was determined by inserting a size 15 K-file into the canal until the tip of the file was just visible at the apical foramen. The canals were accessed and prepared to the apical foramen. The coronal aspect of each canal was flared using Gates Glidden drills (Dentsply Maillefer, Ballaigues, Switzerland) sizes 2-4. All the root canals were prepared with the GT rotary system (Dentsply Maillefer) in a crown-down sequence using a series of size 20 and 30, 0.10-0.04 taper. Between the instruments, each canal was irrigated with 2 mL of a 2% solution of NaOCl, freshly prepared each day, using a syringe and a 27-gauge needle that was placed 1 mm short of the WL. The NaOCl solution was prepared by diluting a 10% NaOCl solution (Merck, Darmstadt, Germany) and its pH adjusted to 10.8 with 1 N HCl. The concentration of the NaOCl solution was measured iodometrically (Moorer & Wesselink 1982). The final file (master apical file, MAF) for each root canal at the foramen was size 30, 0.06 taper. After preparation of the root canal, passive ultrasonic irrigation was performed in group 1 (n=18) with a piezoelectronic unit (PMax:Satelec, Meriganc Cedex, France). After the root canal was filled with 2% NaOCl, using a syringe and a needle, an ultrasonically activated smooth wire of stainless steel size 15, taper 0.02 was inserted in the root canal 1 mm short of WL. The irrigant was ultrasonically activated for 1 minute. Then the root canal was rinsed with 2 mL of 2% NaOCl, using a syringe and a 27-gauge needle that was placed 1 mm short of WL, and the irrigant was again activated ultrasonically for 1 minute. This sequence was repeated three times resulting in a total irrigation time of 3 minutes and a total irrigation volume of 6 mL. The oscillation was performed in bucco-lingual direction at power setting ‘ blue’ 3. According to the manufacturer, the frequency used under these conditions was approximately 30 kHz and the displacement amplitude was 28 μm. The teeth in group two (n=18) were irrigated with 6 mL of 2% NaOCl by syringe irrigation in place of PUI for the same time period.

After ultrasonic irrigation the canals were dried and filled with a warm vertical compaction technique. AH26 silver-free root canal sealer (De Trey Dentsply, Konstanz, Germany) was mixed manually according to the recommendations of the manufacturer. The sealer was placed in the root canals using an EZ-Fill bi-directional spiral (EDS, Hackensack, NJ, USA), 1 mm short of WL in a pumping motion for five seconds. The complete spiral was coated with sealer. Before the filling procedure the tip of a medium sized non-standardized gutta-percha cone (Autofit, Analytic Endodontics, Glendora, CA, USA) was trimmed until tug-back was achieved 0.5 mm short of the full working length. The trimmed gutta-percha cone, lightly coated with sealer, was placed into the canal 0.5 mm short of the WL. At the level of the cementum-enamel junction the gutta-percha was seared off with the tip of an activated heat carrier at 260 degrees (System B, Analytic Technology, Redmond, WA, USA) by placing it in the coronal section of the root canal. After deactivating the heat carrier, the cooled instrument was removed from the canal, bringing out an increment of gutta-percha. Vertical force was then applied with a cold size 11 handplugger (1.1-mm diameter, Dentsply Maillefer) to compact the gutta-percha in the coronal section of the canal. During the application of the plugger care was taken not to contact the canal wall. This procedure was repeated twice, first to a level 3-4 mm deeper than the cementum-enamel junction, vertically compacting the gutta-percha in the middle section of the canal using a cold size 7 plugger (0.7 mm diameter, Dentsply Maillefer), and secondly to the level 4 mm short of the full working length, vertically compacting the gutta-percha in the apical section of the canal using a cold size 5 plugger (0.5 mm diameter, Dentsply Maillefer). After the apical section the middle and the coronal section were filled using the same technique. During the filling procedure two roots of each group were fractured and discarded. The remaining teeth were stored in a moist sponge at 37 °C for one year

Glucose penetration model- preparation and measurements
All samples were examined under a microscope (Zeiss Stemi SV6, Jena, Germany) to exclude those with cracks. The coronal 4 mm of the root specimens were then embedded in Acryl (Vertex, Dentimex BV, Zeist, the Netherlands) to form an acrylic cylinder around the root and enable leak-free contact between the rubber tube and root specimen.

The difference between the current version of the glucose penetration model and the original model introduced by Xu et al. (2005) lies mainly in the environment where the models were stored: in order to prevent evaporation of fluids, the models were placed in a closed jar with 100% humidity. From a pilot study it was concluded that this method would eliminate the effect of fluid evaporation on glucose concentration measurements.

The resin block around the coronal part of each root was connected to a rubber tube and the adaptation improved with stainless steel wires. The other end of the tube was similarly connected to a 16 cm long pipette. The assembly was then placed in a sterile glass bottle with a screw cap and sealed with sticky wax, and a uniform hole drilled in the screw cap with a size 173 diamond bur (Horico, Berlin, Germany) to assure an open system at all times. Two mL of a 0.2% NaN_3 solution was inserted into the glass bottle, such that the root samples were immersed in the solution. NaN_3 was used to inhibit the growth of microorganisms that might influence the glucose readings. The tracer used in the present study was 1 mol/L glucose solution (pH = 7.0). Glucose has a low molecular weight and is hydrophilic and chemically stable. About 4.5 mL of the glucose solution, containing 0.2% NaN_3, was injected into the pipette until the top of the solution was 14 cm higher than the top of GP in the canal, which created a hydrostatic pressure of 1.5 kPa or 15 cm H_2O (Xu et al. 2005)(Figure 1). All specimens were then returned to the incubator at 37 °C for the duration of the observation period. A 25 µL increment of solution was drawn from the glass bottle using a micropipette at 5, 14, 21, 37, 48 and 56 days. The same amount of fresh 0.2% NaN_3 was added to the glass bottle reservoir to maintain a constant volume of 2 mL. The sample was then analyzed with a Glucose kit (Megazyme, Wicklow, Ireland) in a spectrophotometer (Molecular Devices, Spectra max 384 plus, Seattle, Wa, USA) at 340 nm wavelength. Concentrations of glucose in the lower chamber were presented in mg/L at that particular time after obturation. The lowest glucose level for which the current procedure is believed to be accurate is 0.663 mg/L which derives from an absorbance difference of 0.020 (D- Glucose –HK assay procedure, Megazyme International Limited, 2004.) Below this level, the absorbance readings become relatively small, and results are subject to greater error from technique variables. Concentrations smaller than this were thus ignored. Similarly, once leakage exceeded 1.28 g/L samples were no longer tested as the glucose concentration in the lower chamber at this stage was very high and significant leakage had occurred.

The positive control group (n=2) was filled using lateral compaction of GP cones without any sealer. No warm vertical forces were used.

In the negative control group (n=2) all roots were filled with laterally compacted GP and AH 26 and completely covered with nail varnish.

The data were statistically analyzed with the Mann Whitney test and p was set at 0.05.

Results

The results are shown in Table 1 and 2 and Figure 2. After the first month the root fillings in teeth where PUI had been used, sealed the root canal significantly better than in teeth where no PUI had been used (p=0.017).

Discussion

The root fillings placed after PUI allowed significantly less leakage of glucose, which indicates it resulted in a better sealing of the root canal. This can be explained by the fact that more dentine debris can be removed from the oval extensions or irregularities (Lee et al. 2004a) and/or more smear layer can be removed from the canal wall using PUI (Cameron 1983, 1987, Alaçam 1987, Cheung et al. 1993, Huque et al. 1998). When oval extensions or irregularities of the root canal wall are free of dentine debris they can be filled which is likely to result in a better seal of the root filling with probability of reduced or no coronal leakage.

Shaping of the root canal in combination with irrigation is more efficient in cleaning the canal than shaping alone (Baugh et al. 2005). The present study indicates, that efficient irrigation can also result in significant improvement of the sealing of a root filling. This would suggest that efficient irrigation could decrease coronal leakage of the root fillings and thus reduce the nutrition for the biofilm in the root canal with the potential to reduce the occurrence and severity of apical periodontitis (Yamauchi et al. 2006).

Glucose as a marker in leakage studies has clinical relevance because it is an important nutrient for microorganisms and even at very low concentrations a biofilm is able to survive (Siqueira 2001). Because it is impossible to completely remove the biofilm from the root canal (Ricucci et al. 2003, Naïr et al. 2005) leakage of very small amounts of glucose could help the biofilm survive or promote its re-growth when left in the root canal after preparation (Siqueira 2001).

In this study during PUI, 2% NaOCl was placed in the root canal using a syringe in place of a continuous flow. During three minutes of PUI, the 2% solution NaOCl was refreshed every minute using further 2 mL volumes of 2% NaOCl. The results of a previous study showed no significant difference between this method of administration and a continuous flow of irrigant when PUI was used for three minutes (van der Sluis et al. 2006).

The standard deviation of the leakage results of both groups was large. This may have been resulted due to the variation in the oval dimensions of the root canals.

Although the MAF was standardized in all the teeth, the root canal dimension was not standardized; rather the specimens were distributed equally. Another explanation for the large standard deviations in the PUI group can be explained because it is difficult to standardize the positioning of the ultrasonically activated instrument in the center of the root canal and to standardize the displacement amplitude since any constraint on the wire in the canal will change the amplitude. This will have a direct effect on the efficacy of PUI. This could be overcome by increasing the frequency of the ultrasound which will reduce the influence of a variation in the displacement amplitude.

In the present study, the modified glucose penetration model was used (Xu et al. 2005, Shemesh et al. in press). This test can be seen as a further development of the fluid transportation concept (Wu et al. 1993). Both measure penetration of fluid through root fillings after subjecting them to constant pressure; however, the glucose model allows measurements of diffusion of the marker molecules as well. The glucose test might be more sensitive than the measurement of air-bubble movement, not only because the threshold measurement detected by eye is larger than that of the spectrophotometer, but also because the convective fluid transport was combined with glucose molecule diffusion.

Time difference is an important factor when comparing the two different models. In the glucose penetration model the tooth is continuously subjected to the pressure of the glucose solution in the coronal chamber for a period of 2 months. The fluid penetration model detects leakage usually after subjecting the filling to pressure for 3 hours (Shemesh et al. in press). This enormous time difference might make the glucose test more sensitive, as it may result in detection of smaller voids in the filling.

Some authors claim that PUI removes the smear layer completely (Cameron 1985, 1987, Alaçam 1987, Huque et al.1998) or partially from the root canal wall (Cheung et al. 1993) whereas syringe irrigation of NaOCl does not remove the smear layer from the root canal wall (Cheung et al. 1993, Huque et al. 1998). The improved sealing of the root canal filling could also be due to the removal of the smear layer by PUI. However, the reports in the literature on this subject are inconclusive (Sen et al. 1995, Torabinejad et al. 2002).

Leakage along root fillings may increase or decrease with the time following filling. Dissolution of sealer and the smear layer may result in a rise in leakage whereas swelling of GP may result in diminished leakage (Sen et al. 1995, Kontakiotis et al. 1997). The leakage data measured some time after filling the root canals may be clinically more relevant.

Conclusion

Root fillings sealed the root canal better when passive ultrasonic irrigation (PUI) had been used.

Table 1 Mean ± SD of glucose leakage in gram/L at different times

use PUI		day 5	14	21	37	48	57
no	mean	0.19	0.27	0.35	0.61	0.69	0.86
(n=18)	SD	0.34	0.37	0.48	0.46	0.46	0.37
yes	mean	0.05	0.14	0.20	0.30	0.40	0.53
(n=18)	SD	0.08	0.21	0.31	0.42	0.47	0.40

Table 2 The p values of statistic analysis after comparing leakage with and without PUI at the different time intervals

time (days)	P
5	0.440
14	0.274
21	0.970
37	*0.017*
48	*0.045*
57	*0.014*

Figure 1 Schematic representation if the glucose model

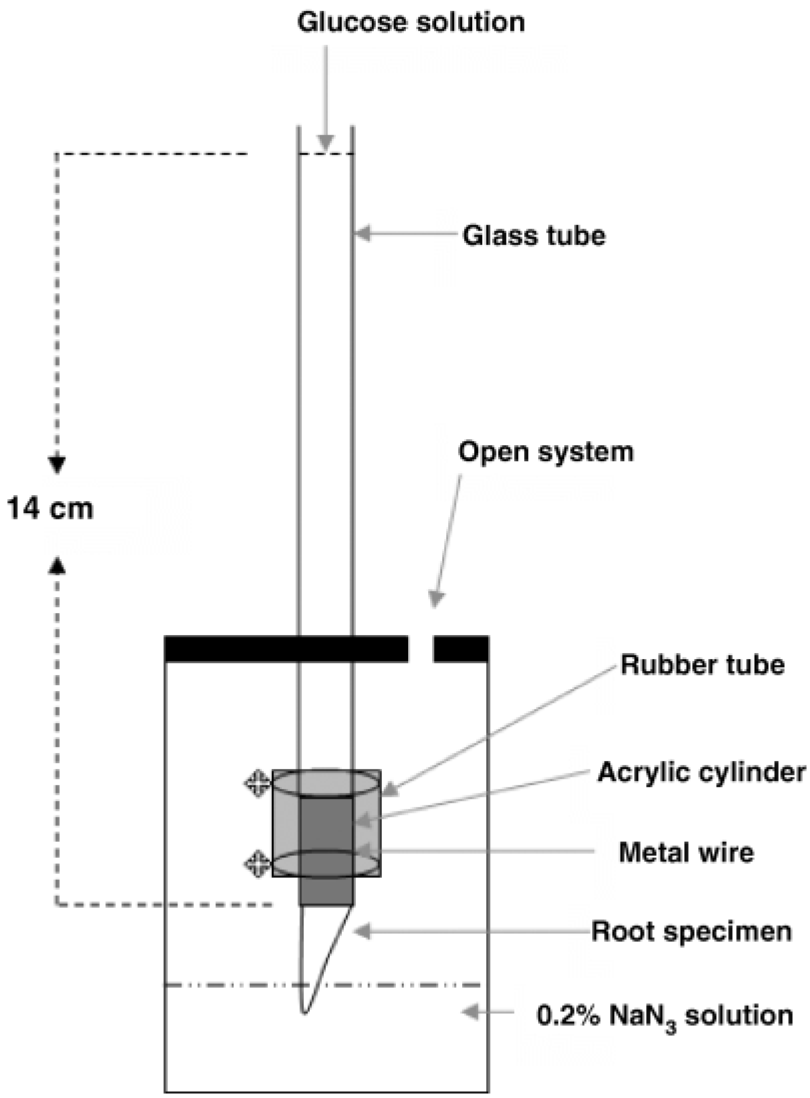
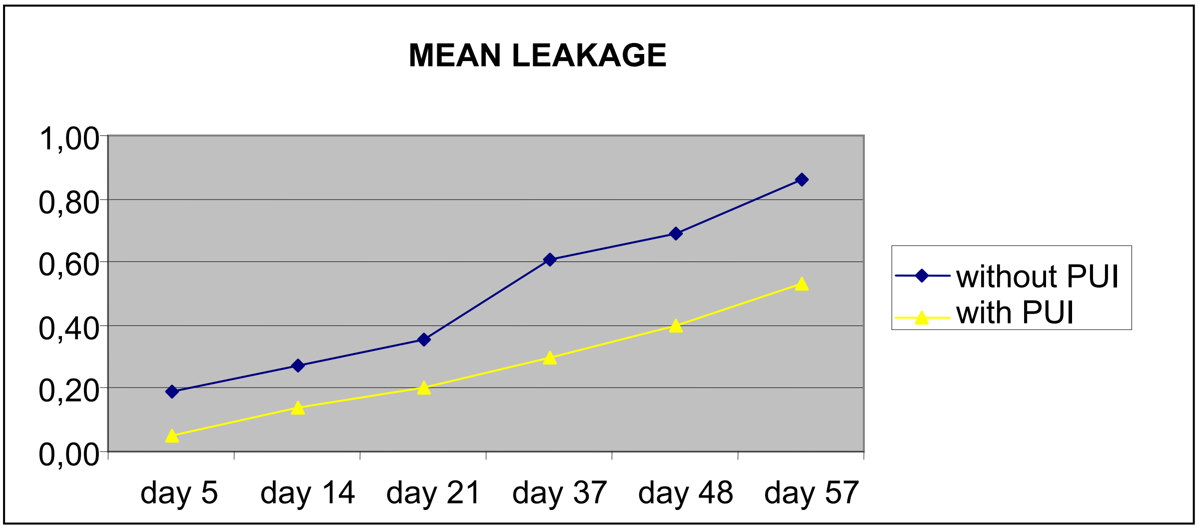


Figure 2 The mean leakage of glucose over time



6

Passive ultrasonic irrigation of the root canal: a review of the literature

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Abstract

Ultrasonic irrigation of the root canal can be performed with or without simultaneous ultrasonic instrumentation. When canal shaping is not undertaken the term passive ultrasonic irrigation (PUI) can be used to describe the technique. In this paper the relevant literature on PUI is reviewed from a Medline database search.

PUI can be performed with a small file or smooth wire (size 10-20) oscillating freely in the root canal to induce powerful acoustic microstreaming. PUI can be an important supplement for cleaning the root canal system and, compared to traditional syringe irrigation, it removes more organic tissue, planktonic bacteria and dentine debris from the root canal. PUI is more efficient in cleaning canals than ultrasonic irrigation with simultaneous ultrasonic instrumentation. PUI can be effective in curved canals and a smooth wire can be as effective as a cutting K file. The taper and the diameter of the root canal were found to be important parameters in determining the efficacies of dentine debris removal. Irrigation with NaOCl is more effective than with water and ultrasonic irrigation is more effective than sonic irrigation in the removal of dentine debris from the root canal. The role of cavitation during PUI remains inconclusive. No detailed information is available on the influence of the irrigation time, the volume of the irrigant, the penetration depth of the instrument and the shape and material properties of the instrument. The influence of irrigation frequency and intensity on the streaming pattern as well as the complicated interaction of acoustic streaming with the adherent biofilm needs to be clarified to reveal the underlying physical mechanisms of PUI.

Introduction

With the endodontic procedures at our disposal it is impossible to shape and clean the root canal completely. This is mainly due to the complex anatomy of the root canal system (Ricucci et al. 2003, Peters 2004, Naïr et al. 2005). Irregularities of the root canal wall in particular are a major concern, including oval extensions, isthmuses and apical delta (Wu&Wesselink 2001, Ricucci et al. 2003, Peters 2004, Naïr et al. 2005). In fact, within oval canals only 40% of the apical root canal wall area can be contacted by instruments when a rotating technique is used (Wu et al. 2003). Therefore, irrigation is an essential part of a root canal treatment as it allows for cleaning beyond the root canal instruments.

The goal of irrigation is to remove pulp tissue and or microorganisms (planktonic or biofilm) from the root canal system (Haapasalo et al. 2005). Irrigation should also remove smear layer and dentine debris that occur following instrumentation of the root canal (Baugh et al. 2005). The efficacy of irrigation depends on the working mechanisms of the irrigant and the ability to bring the irrigant in contact with those elements, materials and structures within the canal system , which have to be removed (Rosenfeld et al. 1978, Chow et al. 1983). Sodium hypochlorite (NaOCl) is widely used as an endodontic disinfectant that is effective because it can dissolve organic tissue, can kill microorganisms, acts as a lubricant and is non-toxic (Haapasalo et al. 2005). However, chlorine, which is responsible for the dissolving and antibacterial capacity of NaOCl, is unstable and is consumed rapidly during the first phase of tissue dissolution, probably within 2 minutes (Moorer & Wesselink 1982); therefore continuous replenishment is essential.

Ultrasonic devices were first introduced in Endodontics by Richman (Richman 1957). Ultrasonically activated files have the potential to mechanical prepare and debride root canals. The files are driven to oscillate at ultrasonic frequencies of 25 to 30 kHz that is beyond the limit of human hearing. The files operate in a transverse vibration, setting up a characteristic pattern of nodes and anti-nodes along their length (Walmsley 1987, Walmsley & Williams 1989). Unfortunately, it proved to be difficult to control the cutting of dentine during ultrasonic preparation, with the result that it is impossible to control the shape of the prepared root canal and apical perforations and irregular shapes were produced (Stock 1991, Lumley et al. 1992, Sundqvist & Figdor 1998).

On the other hand it has been shown that ultrasonically driven files are effective for the irrigation of root canals. Two types of ultrasonic irrigation have been described in the literature: one where irrigation is combined with simultaneous ultrasonic instrumentation (UI) and another without simultaneous instrumentation, so called passive ultrasonic irrigation (PUI). During UI the file is intentionally brought into contact with the root canal wall. UI has been shown to be less effective in removing simulated pulp tissue from the root canal system or smear layer from the root canal wall than PUI (Weller et al. 1980, Ahmad et al. 1987a). This can be explained by a reduction of acoustic streaming and cavitation (Ahmad et al. 1987a). Since the root canal anatomy is complex (Peters 2004) an instrument will never contact the entire root canal wall (Wu et al. 2003). Thus, UI could result in uncontrolled cutting of the root canal wall without effective cleaning.

PUI was first described by Weller et al. (1980). The term ‘passive’ does not adequately describe the process, as it is in fact active; however, when it was first introduced the term ‘passive’ related to the ’non-cutting’ action of the ultrasonically activated file. PUI relies on the transmission of acoustic energy from an oscillating file or smooth wire to an irrigant in the root canal. The energy is transmitted by means of ultrasonic waves and can induce acoustic streaming and cavitation of the irrigant (Ahmad et al. 1987a-b, Ahmad et al. 1988, Lumley et al. 1991, Ahmad et al. 1992, Roy et al. 1994). After the root canal has been shaped to the master apical file (irrespective of the preparation technique used), a small file or smooth wire (for example size 15) is introduced in the centre of the root canal, as far as the apical region. The root canal is then filled with an irrigant solution and the ultrasonically oscillating file activates the irrigant. Since the root canal has already been shaped, the file or wire can move freely and the irrigant can penetrate more easily into the apical part of the root canal system (Krell et al. 1988) and the cleaning effect will be more powerful (Ahmad et al. 1987a-b, Ahmad et al. 1988, Ahmad et al. 1992, Lumley et al. 1991, Roy et al. 1994). Using this non-cutting methodology the potential to create abberant shapes within the root canal will be reduced to a minimum. A file larger then size 15 or 20 will only oscillate freely in a wide root canal. A size 25 file may in fact produce less acoustic streaming than a size 15 and 20 file (Ahmad et al. 1987b). Consequently, using a file larger than size 20 may be considered fundamentally different from the basic principle of PUI. The cleaning efficacy of PUI implies the effective removal of dentine debris, microorganism (planktonic or in biofilm) and organic tissue from the root canal. Due to the active streaming of the irrigant its potential to contact a greater surface area of the canal wall will be enhanced.

The purpose of this review is to evaluate the literature on PUI and to provide a description of the mechanism and its effects, and if PUI is more effective than syringe irrigation.

Materials and methods

The literature search used the MEDLINE database which goes back to 1965. Reference lists of potentially relevant articles and review articles were also screened for the search strategy. The following combinations of keywords were used for the search strategy:

- “ultrasound irrigation root canal”
- OR “ultrasonic irrigation root canal”
- OR “passive ultrasonic irrigation”
- OR “ultrasound NaOCl”
- OR “ultrasonic cavitation root canal”
- OR “ultrasonic acoustic streaming root canal”
- OR “ultrasonic bacteria root canal”
- OR “ultrasonic biofilm root canal’’ .

Care was taken to only include studies that addressed *passive* ultrasonic irrigation; studies using UI were excluded. It appeared that there is little consensus about the terminology of ultrasonic irrigation in the literature. For example, PUI occasionally was mentioned, while in fact UI was meant. Such discrepancies potentially had a considerable influence on the interpretation of the results of PUI. The papers were screened independently by two reviewers (M-K. W. and L.S.). The quality of the papers was assessed including an evaluation of the study design and statistical tests. Some papers were categorized as observational studies. These studies describe in detail acoustic streaming patterns, cavitation or displacement amplitudes of the file or wire (Cameron 1987, Ahmad et al. 1987a-b, Lumley et al. 1988, Cameron 1988, Walmsley & Williams 1989, Ahmad M 1989, Ahmad M 1990, Lumley et al. 1991, Lumley & Walmsley 1992, Ahmad et al. 1992, Ahmad et al. 1993, Roy et al. 1994, Cameron 1995, Lea et al. 2004). Also three review articles on ultrasonic irrigation cleaning were included: Walmsley (1987), Walmsley et al. (1991) and Stock (1991).

The search resulted in a total of 74 articles of which 19 were excluded because they did not correspond with the inclusion criteria. The articles were UI in place of PUI was used are listed in table one.

Different frequencies, intensities and displacement amplitudes of the files were used in the various studies. Whether these parameters influenced the results reported is not known. Other variables that are encountered in laboratory research, e.g. the difference in preoperative status of the teeth, storage media and storage time may also have an influence on the outcome. However their effect is unknown.

Results

The results of the review are divided in two parts. The first part describes the mechanism of PUI, the second part the effects of PUI.

Mechanism of PUI

Frequency and intensity

An ultrasonic device converts electric energy into ultrasonic waves of a certain frequency by magnetostriction or by piezoelectricity. Magnetostriction is generated by the deformation of a ferromagnetic material subjected to a magnetic field, piezoelectricity on the other hand is the generation of stress in dielectric crystals subjected to an applied voltage. Piezoelectricity was used in the studies of Goodman et al. (1985), Ahmad et al. (1992) and (1993), Cheung & Stock (1993), Lee et al. (2004a-b) and van der Sluis et al. (2005a-b), (2006). Only one pilot study was undertaken to compare devices using magnetostriction or piezoelectricity at different intensities, however, no conclusive evidence was provided (Cameron 1995).

The properties of the ultrasonic material determine the frequency of the oscillating instrument, which in dental practice, is fixed at 30 kHz. The intensity or energy flux, expressed in units of Watt/cm^2, of the oscillating instrument can be adjusted by the power setting. Frequency and intensity do play a role in the transmission of energy from the ultrasonically oscillating file to the irrigant but a full understanding of the mechanism is still lacking. A higher frequency should in principle result in a higher streaming velocity of the irrigant, as will be addressed later. This in turn results in a more powerful acoustic streaming. Increasing the intensity does not result in a linear increase of the displacement amplitude of the oscillating file (Ahmad et al. 1987a, Walmsley & Williams 1989, Lea et al. 2004). However, this observation is taken from studies that investigated the oscillation of the file in free air. Therefore, a direct relationship with acoustic microstreaming could not be established.

Acoustic streaming

Acoustic streaming is the rapid movement of fluid in a circular or vortex-like motion around a vibrating file (Walmsley 1987). The acoustic streaming that occurs in the root canal during ultrasonic irrigation has been described as acoustic microstreaming. This is defined as the streaming which occurs near small obstacles placed within a sound field, near small sound sources, vibrating membranes or wires, which arise from the frictional forces between a boundary and medium carrying vibrations of circular frequency (Leighton 1994).

Several papers have confirmed that acoustic microstreaming occurs during PUI (Ahmad et al. 1987a-b, Walmsley 1987, Walmsley & Williams 1989, Lumley et al. 1991, Walmsley et al. 1991, Ahmad et al. 1992, Ahmad et al. 1993, Lumley et al. 1993, Roy et al. 1994) (Fig.1). The streaming pattern corresponds to the characteristic pattern of nodes and anti-nodes along the length of the oscillating file.

The displacement amplitude is at its maximum at the tip of the file, probably causing a directional flow to the coronal part of the root canal (Ahmad et al. 1987a). When the file touches the root canal wall at an antinode a greater reduction in displacement amplitude will occur compared to when it touches at a node (Walmsley & Williams 1989, Lumley et al. 1993). When the file is unable to vibrate freely in the root canal, acoustic microstreaming will become less intense, however, it will not stop completely (Ahmad et al. 1988, Ahmad et al. 1992, Lumley et al. 1991, Lumley et al. 1993, Roy et al. 1994). The resultant acoustic microstreaming depends inversely on the surface area of the file touching the root canal wall.

In curved canals, prebending the file will result in more powerful acoustic microstreaming (Ahmad et al. 1992, Lumley & Walmsey 1992, Lumley et al. 1992). A prebent file shows the same pattern of nodes and antinodes as a straight file both in air and in the confined geometry of a root canal (Lumley & Walmsey 1992).

The intensity of the acoustic microstreaming is directly related to the streaming velocity. The equation that in first approximation describes the streaming velocity is

$$v = \frac{\omega \varepsilon_0^{\ 2}}{a} \qquad (1)$$

where v is the liquid streaming velocity, ω is 2π times the driving frequency, ε_0 is the displacement amplitude and a the radius of the wire. Following Eq. 1 it can be concluded that the thinner the file, the higher the frequency and the greater the displacement amplitude of the file, the higher the streaming velocity and the more powerful the acoustic microstreaming will be. Whether this equation will also hold for the complicated non-linear streaming pattern during PUI remains to be shown.

The shear flow caused by acoustic microstreaming produces shear stresses along the root canal wall, which can remove debris and bacteria from the wall. The shear stress is expressed in the following equation (Ahmad et al. 1988):

$$\tau = \eta \cdot \dot{\gamma} = \eta \cdot \frac{V}{\delta} = \frac{\eta \omega \varepsilon_0^{\ 2}}{a\delta} \qquad (2)$$

where η the kinematic viscosity of the liquid, V the streaming velocity (from Eq. 1) and δ the boundary layer thickness. This equation is an approximation and it remains to be shown whether it is applicable to the typical, more complex, flow conditions of the root canal.

Cavitation and cavitational microstreaming

Cavitation in the fluid mechanical context can be described as the impulsive formation of cavities in a liquid through tensile forces induced by high-speed flows or flow gradients. These bubbles expand and than rapidly collapse producing a focus of energy leading to intense sound and damage, e.g. pitting of ship propellers and pumps. Acoustic cavitation can be defined as the creation of new bubbles or the expansion, contraction and /or distortion of pre-existing bubbles (so-called nuclei) in a liquid, the process being coupled to acoustic energy (Leighton 1994). Cavitation is beneficially used in industrial ultrasound cleaning (Moholkar et al. 2004), megasonic chip cleaning (Kern 1990), lithotripsy (Church 1989) and even by small shrimp to stun prey (Versluis et al. 2001). In this review the term cavitation refers to acoustic cavitation.

According to Roy et al. (1994) two types of cavitation could occur during PUI of root canals: stable cavitation and transient cavitation. Stable cavitation could be defined as linear pulsation of gas-filled bodies in a low amplitude ultrasound field. Transient cavitation occurs when vapour bubbles undergo highly energetic pulsations (Fig.2). When the acoustic pressures are high enough, the bubbles can be inertially driven to a violent collapse, radiating shock waves and generating high internal gas pressures and temperatures. The energy at the collapse point is in some cases sufficient to dissociate the gas molecules in the bubble, which recombine radiatively to produce light, a process known as sonoluminescence (Crum 1994, Brenner et al. 2002). In the studies of Ahmad et al. (1988), Lumley et al. (1993) and Roy et al. (1994) sonoluminescence was used to detect transient cavitation.

Transient cavitation only occurs when the file can vibrate freely in the canal or when the file touches lightly (unintentionally) the canal wall (Lumley et al. 1993, Roy et al. 1994). Increased (intentional) contact with the canal wall, as in UI, excludes transient cavitation. The surface property of the file is important for the enhancement of cavitation (Roy et al. 1994). In their study a smooth file with sharp edges and a square cross-section produced significantly more transient cavitation than a normal K-file. The sharp edges could have induced so-called edge cavitation. The transient cavitation was visible at the apical end and along the length of the file. When the file came in contact with the canal wall, stable cavitation was affected less than transient cavitation and was mainly seen at the midpoint of the file (Roy et al. 1994). A prebent file brought into a curved canal is more likely to produce transient cavitation rather than a straight file (Roy et al. 1994). Other researchers claim that cavitation provides only minor benefit in ultrasonic irrigation, or that it does not occur at all (Walmsley 1987, Ahmad et al. 1988, Lumley et al. 1988).

The effects and use of PUI

PUI versus syringe irrigation

After shaping the root canal cleaning can be completed with PUI or a final flush of syringe irrigation. From the studies where PUI and syringe irrigation were compared it can be concluded that PUI is more effective in removing remnants of pulp tissue and dentine debris (Goodman et al. 1985, Cameron 1987a, Metzler & Montgomery 1989, Cheung & Stock 1993, Lee et al. 2004b, Gutarts et al. 2005, Passarinho-Neto et al. 2006) and planktonic bacteria (Sjögren & Sundqvist 1987, Huque et al. 1998, Spoleti et al. 2003, Weber et al. 2003)(Fig.3). In the studies by Goodman et al. (1985), Cheung & Stock (1993), Spoleti et al. (2003), Gutarts et al. (2005), Passarinho-Neto et al. (2006) the working volume of the experimental irrigant was standardized between the groups. In all these studies NaOCl was used as the irrigant except the study of Spoleti et al. (2003) and Weber et al. (2003) where sterile saline and chlorhexidine and NaOCl was used respectively.

In the study of Mayer et al. (2002) no significant difference was found between PUI and syringe irrigation in dentine debris removal from the root canal. Before activating ultrasonically the NaOCl, EDTA was left in the root canal. Removal of EDTA before the injection of 2 mL NaOCl in the root canal was not mentioned. EDTA inactivates the NaOCl and it is possible that this had an influence on the outcome.

PUI with NaOCl as irrigant

During PUI, NaOCl removes significantly more smear layer or bacteria from artificial smear layer, pulp tissue or dentine debris from the root canal than water (Cameron 1987b, Metzler & Montgomery 1989, Cheung & Stock 1993, Heard&Walton 1997, Türkün & Cengiz 1997, Huque et al. 1998, van der Sluis et al. 2006a). The significant increase in dissolving capacity of organic material by NaOCl, when NaOCl is agitated by ultrasound (Moorer &Wesselink 1982) or when the temperature rises because of ultrasound (Cunningham & Balekjian 1980, Cameron 1988, Ahmed 1990) can be an explanation for the enhanced performance of NaOCl. When a greater concentration of NaOCl is used the efficacy appears to increase (Türkün & Cengiz 1997, Huque et al. 1998).

Removal of bacteria

PUI results in a significant reduction of bacteria (Martin 1976, Collinson & Zakariasen 1986, Ahmad 1989), or shows significantly better results than syringe irrigation (Sjögren & Sundqvist 1987, Huque *et al.* 1998, Spoleti *et al.* 2003, Weber *et al.* 2003). Only in the study of Siqueira *et al.* (1997) was the difference not significant. In the study by Huque *et al.* (1998), PUI with 12% NaOCl as irrigant almost completely removed different types of planktonic bacteria from a parallel sided canal by a streaming effect through the dentinal tubules.

Studies on the antibacterial effect of PUI have focused on the removal of planktonic bacteria through the flushing effect. The physical mechanisms describing the effect of ultrasonic irrigation on biofilms in the root canal are unknown, although cavitation has shown to be able to destroy or even remove a biofilm (Ohl *et al.* 2006).

Removal of the smear layer

Studies on smear layer removal by PUI are inconclusive. However, the various studies selected different types and concentrations of irrigant solution. When 3% NaOCl was used Cameron (1983) found complete removal of smear layer with three and five minutes of PUI; the results were confirmed in a subsequent study (Cameron 1987b). Alaçam (1987) could completely remove the smear layer after three minutes of PUI with 5% NaOCl and Huque et al. (1998) after 20 seconds PUI with 12% NaOCl. A 5% NaOCl solution during 3 minutes PUI could remove more smear layer than 0.5% NaOCl from the apical and middle part of the root canal (Türkün & Cengiz 1997). Cheung & Stock (1993) could not completely remove the smear layer using 10 seconds PUI with 1% NaOCl, although PUI was significantly better than syringe irrigation. In the studies of Ciucchi et al. (1989) and Abbott et al. (1991) ultrasound did not enhance the removal of the smear layer when EDTA or a combination of EDTA and NaOCl was used as irrigant. On the other hand PUI could significantly improve the smear layer removal of Savlon (0.03% chlorhexidine, 0.3% cetrimide). PUI with water as irrigant is unable to remove the smear layer (Cameron 1983, Cameron 1987b, Heard & Walton 1997, Türkün & Cengiz 1997, Huque et al. 1998). All studies show increased removal of the smear layer primarily from the coronal part of the root canal wall rather than the apical part, except for one study (Türkün & Cengiz 1997).

All these studies used the SEM technique to investigate the presence of smear layer. A disadvantage of this methodology is that only a very small part of the root canal can be evaluated and this is often not standardised.

PUI in curved canals

PUI can also be effective in curved canals (Goodman et al. 1985, Metzler & Montgomery 1989, Jensen et al. 1999, Sabins et al. 2003, Gutarts et al. 2005) and the best result is obtained when the file is prebent (Ahmad et al. 1992, Lumley & Walmsey 1992). In the studies of Goodman et al. (1985), Metzler & Montgomery (1989), Jensen et al. (1999), Sabins et al. (2003), Gutarts et al. (2005) the apical portion of the root canal was examined, i.e. below the curve. When compared with syringe irrigation (Goodman et al. 1985, Metzler & Montgomery 1989, Gutarts et al. 2005) PUI performed significantly better.

PUI and the cleaning of the isthmus

Some studies specifically evaluated the cleaning efficacy of PUI in the isthmus which runs between two canals. Their results confirm a significantly cleaner isthmus when PUI is used compared to syringe irrigation (Goodman et al. 1985, Metzler & Montgomery 1989, Gutarts et al. 2005), which demonstrates that PUI has the potential to remove pulp tissue and dentine debris from remote areas of the root canal system untouched by endodontic instruments.

Ultrasonic versus sonic irrigation

Sonic irrigation is different from ultrasonic irrigation because it operates at a lower frequency. For sonic application the frequencies ranges from 1000 to 6000 Hz. Consequently, following Eq. 1, the streaming velocity of the irrigant will be lower. Also the oscillating patterns of the sonic instruments are different. They have one node near the attachment of the file and one antinode at the tip of the file. When the movement of the sonic file is constrained the sideway movement will disappear, but will result in a longitudinal vibration (Lumley et al. 1996).

Two studies report that PUI removed more dentine debris from the root canal than sonic irrigation (Stamos et al. 1987, Sabins et al. 2003), while in one study no significant difference was found (Jensen et al. 1999). In the study by Jensen et al. (1999), however, prebending of the files was not mentioned and this may explain their findings. The positive relationship between streaming velocity and frequency can explain the higher efficiency of PUI versus sonic irrigation.

Heating of irrigant and root surface during PUI

Cameron (1988) reported a rise of the intracanal temperature from 37°C to 45°C close to the tip of the instrument and 37 °C away from the tip when the irrigant was ultrasonically activated for 30 seconds without replenishment. A cooling effect from 37°C to 29°C was recorded when the irrigant was replenished with a continuous flow of irrigant. The temperature of the irrigant was 25°C. The external temperature stabilized at 32°C during a continuous flow of the irrigant and reached a maximum of 40°C in 30 seconds without continuous flow. Ahmad (1990) reported a mean rise of temperature of 0.6°C during a continuous flow of irrigant. The initial temperature of the irrigant was 20°C. A rise of temperature within these ranges will not cause pathological temperature rises in the periodontal ligament.

PUI Parameters

Taper of the file and diameter of the root canal.

The taper and diameter of the root canal have an influence on the efficacy of PUI in dentine debris removal from the root canal. In the studies by Lee et al. (2004a) and van der Sluis et al. (2005b), three minutes of PUI with 2% NaOCl was performed in each canal. From their results it can be concluded that within certain limits (size 20, taper 0.04 to size 20, taper 0.10) the greater the taper the more dentine debris can be removed.

Application of irrigant during PUI

Two flushing methods can be used during PUI, namely a continuous flush of irrigant from the ultrasonic handpiece or an intermittent flush method using syringe delivery (Cameron 1988). In the intermittent flush method, the irrigant is injected into the root canal by a syringe, and replenished several times after each ultrasonic activation. During ultrasonic activation, an ultrasonically oscillating instrument (file or smooth wire) will activate the irrigant in the root canal such that micro-organism, dentine debris and organic tissue will be detached from the root canal wall and be absorbed or dissolved in the irrigant (Weller et al. 1980, Moorer & Wesselink 1982). Hereafter the root canal is flushed with 2 mL of fresh irrigant to remove the remnants from the root canal. Both flushing methods were equally effective in removing dentine debris from the root canal in an ex vivo model when the irrigation time was set at three minutes (van der Sluis et al. 2006a).

Druttman & Stock (1989) concluded that using a continuous flush of irrigant, the irrigant replacement in the root canal system is more likely to be influenced by time than by the volume used (Druttman & Stock 1989). This is confirmed by a study of Passarinho-Neto et al. (2006) were 5 minutes of PUI removed more dentine debris from the root canal than 1 minute using a continuous flow of NaOCl, when the volume was the same in both groups. When the irrigant is injected in the root canal by a syringe the amount of irrigant flowing through the apical region of the canal can be controlled because both volume and depth of syringe penetration are known, this is not possible using the continuous flush from the handpiece. The apical flow is important because frequent replenishment of NaOCl is essential.

Irrigation time

The influence of irrigation time on the efficacy of PUI is not clear. One study claimed an increased removal of the smear layer after 5 minutes of PUI as opposed to 3 minutes (Cameron 1983). In the study of Sabins et al. (2003) no significant difference was found between 30 and 60 seconds of PUI in dentine debris removal from the root canal. In their study, instead of a continuous flow of NaOCl during PUI, the NaOCl was injected in the root canal by a syringe and not refreshed during the ultrasonic activation of NaOCl.

PUI with a smooth wire

A smooth wire is as effective as a normal cutting file in dentine debris removal during PUI (van der Sluis et al. 2005a). It seems preferable to use a smooth wire during PUI because it does not intentionally cut into the root canal wall and it may therefore prevent aberrant root canal shapes or perforation of the (apical) root (Mayer et al. 2002). Several studies (Weller et al. 1980, Cameron 1983, Goodman et al. 1985, Cameron 1987, Türkün & Cengiz 1997, Mayer et al. 2002, Gutarts et al. 2005) have used smooth wires, and demonstrated their effectiveness during PUI. The smooth wire used in the study by Gutarts et al. (2005) was in fact a hollow ultrasonically activated needle through which the irrigant was delivered into the root canal.

Discussion

Acoustic microstreaming or cavitation play an important role in the efficacy of PUI. However, the details concerning those mechanism have not been clarified. An accurate description of the streaming pattern of the irrigant in the root canal during PUI for instance is still not available. Therefore, the exact physical mechanisms responsible for the efficacy of PUI remain uncertain.

In some of the studies large standard deviations have been reported, indicating a substantial variation in the efficacy of PUI. An explanation could be that it is difficult to standardize the positioning of the ultrasonically activated instrument in the centre of the root canal and to standardize the displacement amplitude since a small constraint in the canal will change the amplitude. This will have a direct effect on the efficacy of PUI. This problem can most probably be overcome by increasing the frequency of the ultrasound. Then the streaming velocity of the irrigant will be so strong that a small change in the position of the instrument will make little difference.

Water as the irrigant appears to be less efficient than NaOCl during PUI. The differences in the physical properties of NaOCl and water could have an effect on the transmission of ultrasound energy by to the irrigant. For example, bubbles formed in salt water tend to be more numerous, particularly the smallest bubbles, and are less prone to coalesce than bubbles in fresh water (Leighton 1994). Vapour (chloride when NaOCl is used) could diffuse into the bubble during bubble expansion and the bubble dynamics depend on the concentration of the gas dissolved in the liquid, the temperature of the liquid and amounts of surface-active impurities (Brenner et al. 2002). These factors may explain why PUI with sterile saline (0.9% NaCl) removed significantly more planktonic bacteria from the root canal than syringe irrigation of saline although saline does not dissolve organic tissue and is not bactericidal (Spoleti et al. 2003). Water did not show a significant difference in the removal of dentine debris or planktonic bacteria when syringe irrigation and PUI were compared (Walker & Rio 1989, Cheung & Stock 1993, Huque et al. 1998).

Subject to debate is the efficacy of PUI in curved canals. In the papers discussed in this review, the curvature of the roots was moderate <35 (Schneider 1971) and therefore prebending of the file was possible, which may in part explain the positive results. Another explanation could be that PUI is performed after the root canal has been shaped. Therefore, the apical root canal is widened and there is simply more space for the file to move freely in the irrigant, even when the ultrasonically activated instrument does not reach the full working length (Krell et al. 1988). Furthermore, Roy et al. (1994) showed that transient cavitation could occur in curved canals (but only when the file was prebend) creating a highly active streaming pattern in curved canals.

Conclusion

Based on this literature review it is concluded that PUI appears to be an adjunctive treatment for cleaning the root canal system and that PUI is more effective than syringe irrigation. More research is needed to clarify the underlying physical mechanisms through which PUI exerts its efficacy.

Figure 1
Acoustic streaming around a file in free water (left) and a schematic drawing, modification after Ahmad et al. 1987a JOE 13, 490-9 (right).

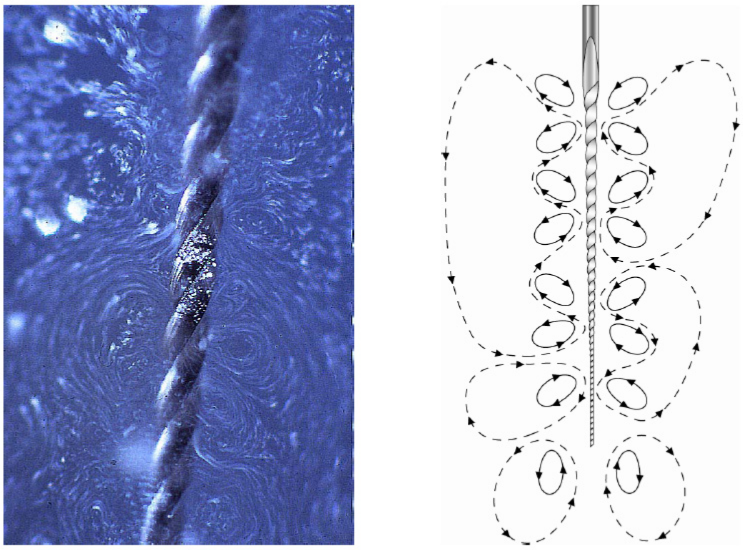


Figure 2
Left: Glass root canal model allowing optical access to the vibrating file for high-speed visualization of ultrasonic irrigation. Middle: file in operation captured at microseconds timescale displaying both transient and inertial cavitation phenomena and in addition local streaming patterns (only visible in video mode). To the right a high-speed recoding of a non cutting K-file is shown, displaying vigorous microstreaming and collapsing cavitation bubbles.

Figure 3
Dentine debris packed in oval shaped root canal after syringe irrigation (left) and clean oval canal after 3 minutes of PUI (right).

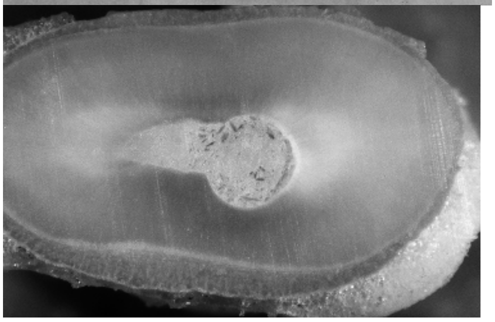


Table 1

Articles which were not included because they dealt with UI and not PUI
Cunningham (1982), Langeland et al. (1985), Barnett et al. (1985), Chenail &Teplitsky (1985), Griffiths & Stock (1986), Krell & Johnson (1988), Haidet et al. (1989), Rodrigues & Biffi (1989), Walker& del Rio(1989), Biffi & Rodriques (1989), Briseno et al. (1992), Archer et al. (1992), Baumgartner & Cuenin (1992), Lumley et al. (1992) and (1993), Panighi & Jacquot (1995), Siqueira et al. (2002), Guerisoli et al. (2002), Walters et al. (2002).

7

A comparison between a smooth wire and a K-file in removing artificially placed dentine debris from root canals in resin blocks during ultrasonic irrigation

In International Endontic Journal 2005; **38**, 593-6.

L. W. M. van der Sluis, M.-K. Wu & P. R. Wesselink

Abstract

Aim To compare the efficacy of a smooth wire with a conventional K-file, in removing dentine debris from grooves in root canals made in resin blocks, during ultrasonic irrigation.

Methodology Each resin block containing a standard simulated canal was split longitudinally through the canal, forming two halves. In one canal wall, a standard groove 4 mm in length, 0.2 mm in width and 0.5 mm in depth was cut 2–6 mm from the apical end of the canal, to simulate uninstrumented canal extensions. Each groove was filled with fresh dentine debris mixed with 2% NaOCl to simulate a situation when dentine debris accumulates in uninstrumented canal extensions. Each canal was reassembled by joining the two halves of the resin block by means of wires and sticky wax. In each canal ultrasonic irrigation was performed for 3 min using 2% NaOCl as irrigant. In one group ($n = 20$) a conventional K-file size 15 was used. In the other group ($n = 20$) a smooth wire was used which had the same length and diameter as the size 15 K-file. Before and after irrigation, images of each half of the canal with a groove were taken, using a microscope and a digital camera, after which they were scanned into a PC as TIFF images. The quantity of dentine debris in the groove was evaluated using a scoring system: the higher the score, the larger the amount of debris remaining. The score data were analysed by means of the Mann–Whitney *U*-test.

Results After ultrasonic irrigation, the debris was completely removed from the groove in 35 canals (87.5%), and there was no significant difference between the groups ($p=0.429$).

Conclusions Using a smooth wire during ultrasonic irrigation is as effective as a size 15 K-file in removal of artificially placed dentine debris in grooves in simulated root canals in resin blocks.

Introduction

Ultrasound is sound energy with a frequency above the limit of human hearing (>20 kHz). Ultrasonic devices have been used in dentistry mainly in Periodontics until Richman introduced ultrasound into Endodontics as a means of canal debridement (Richman 1957). In Endodontics ultrasound can be used for preparing root canals because of its cutting action, and/or irrigation because it can induce acoustic streaming of irrigant solutions. Because it is difficult to control the cutting of dentine during ultrasonic preparation, canal transportation can occur and the root canal wall is not smooth after preparation (Stock 1991, Sundqvist & Figdor 1998). This uncontrolled action of the file during ultrasonic preparation is the reason why ultrasound is not routinely used for shaping.

The cleaning efficacy of ultrasound appears to be promising when it is used only for irrigation after the root canal has been instrumented (Ahmad et al. 1987). Compared with hand irrigation, ultrasonic irrigation is effective (Cunningham et al. 1982, Goodman et al. 1985, Haidet et al. 1989, Lee et al. 2004a,b). In laboratory studies (Lee et al. 2004a,b) standard grooves or holes were made in root canals in prepared extracted teeth or resin blocks to simulate oval canal extensions or canal irregularities. These grooves or holes were filled with dentine debris and after hand- or ultrasonic irrigation the amount of dentine debris still present in the grooves or holes was evaluated. Using this method it was clear that ultrasound irrigation was more effective than syringe irrigation and that artificially made root canals in resin blocks with a diameter of 0.20 mm and 06 and 08 taper were significantly cleaner than root canals with a diameter of 0.20 mm and 04 taper.

Acoustic streaming is the most acceptable explanation for the cleaning efficacy of ultrasonic irrigation (Ahmad et al. 1987). The stronger the streaming the better the result (Lumley et al. 1991). The streaming velocity produced by ultrasonic irrigation produces hydrodynamic shear stresses, which are more than capable of disaggregating clumps of bacteria or debris contained within the canal (Lumley et al. 1991). Acoustic streaming is defined as the generation of time-independent, steady unidirectional circulation of fluid in the vicinity of a small vibrating objects (Nyborg 1965). The prerequisite of an effective acoustic streaming is the free vibration of the instrument in the root canal (Ahmad et al. 1987). The streaming velocity is described by the formula

$$Um = \omega\varepsilon^2_0/a$$

in which Um is the liquid streaming velocity, ω is 2π times the driving frequency, ε is the displacement amplitude and a the radius of the wire (Ahmad et al. 1987). According to the formula: (1) the diameter of the file (a), (2) the amplitude displacement (ε^2_0) and (3) the frequency (f) are important for the efficacy of the ultrasonic irrigation. The best effect is obtained when the wire is small, the amplitude displacement is large and the frequency is high. The diameter of the canal is important because it can influence the amplitude displacement.

Another factor of importance is the heat generated by ultrasound. Ultrasound can increase the temperature of a 2.5% solution of sodium hypochlorite to a level comparable with the tissue dissolving effectiveness of a 5% solution of sodium hypochlorite (Cunningham & Balekjian 1980). The frequency and the displacement amplitude will have an effect on the heating of the sodium hypochlorite. By increasing the frequency and the displacement amplitude the temperature of the sodium hypochlorite will rise and the tissue dissolving effectiveness of the sodium hypochlorite will be enhanced.

According to the formula the diameter of the root canal is critical and for this reason it was important to use resin blocks to standardize the diameter of the root canal. It is not possible to standardize the diameter of root canal preparation in natural teeth because the difference in diameter is too large (Stock 1991).

Normally in ultrasonic irrigation a size 15 K-file is used but the action of the file can result in a canal wall which is not smooth, in canal transportation or apical perforation. According to the formula it would be possible to replace the K-file with a smooth wire without reducing the cleaning efficacy as long as the diameter of the wire is the same as the file. For this reason the purpose of the study was to compare the efficacy of a smooth wire, in removing artificially placed dentine debris from straight root canals made in resin blocks, with a normal K-file, during ultrasonic irrigation.

Materials and methods

Forty resin blocks (Endo Training Block, REFA0177; Dentsply Maillefer, Ballaigues, Switzerland) were used. The original straight root canal was enlarged using a size 20,0.8 rotary GT instrument (Dentsply Maillefer) in a handpiece rotating at approximately 300 rpm. Two grooves were then cut in each block along the long axis of the canal, before splitting longitudinally through the canal using a chisel, forming two halves.

The working portion of a hand spreader (A60; Dentsply Maillefer) was removed and the end of the shank was sharpened. In the wall of one half of each canal, a standard groove 4 mm in length was created 2–6 mm from the apex using this modified hand spreader (Fig. 1); the groove simulated an uninstrumented canal extension. The groove was 0.2 mm wide and 0.5 mm deep, the width of the groove is comparable with the width of the short diameter of narrow oval canals (Wu et al. 2000).

To produce dentine debris, a number of freshly extracted teeth were split longitudinally and debris was ground from the canal wall with round burs from the pulpal side to the cementum side. Five minutes before use, the dentine debris was mixed with 2% NaOCl and a wet sand-like mixture was prepared. Using a paper point, each groove was filled with debris taking care not to compact it.

To reassemble the tooth, the two halves of each block were reconnected using wires and sticky wax. Two groups of 20 canals were used. Ultrasonic irrigation was performed in each canal with a piezo-electronic ultrasonic unit (P MAX; Satelec, Meriganc Cedex, France) using 2% NaOCl as the irrigant. The concentration of the NaOCl solution was measured iodometrically (Moorer & Wesselink 1982). In group 1, each canal was then irrigated with approximately 200 mL of 2% NaOCl along an ultrasonically activated size 15 K-file to 1 mm short of the apical end of the canal, and oscillating in the direction towards the groove at speed 3 for 3 min. According to the manufacturer, the frequency employed under the above-mentioned conditions was approximately 30 kHz. In group 2, the same procedure was followed as in group 1, only a smooth wire size 15 was used, with the same properties as the size 15 K-file, during the ultrasonic irrigation. The smooth wire was made by grinding and polishing a size 25 K-file until it was smooth and had the same dimensions as the size 15 K-file.

Before and after irrigation, photographs of the two halves of the canal were taken using a Photomakroskop M 400 microscope with a digital camera (Wild, Heerbrugg, Switzerland) at ×40 magnification; the photos were then scanned as tagged-image file format images. The amount of debris in the grooves was evaluated prior to treatment, using a scoring system, in order to examine whether all grooves were filled with debris at the time of irrigation. The second scoring was performed after irrigation. A higher score indicated a greater amount of debris: score 0: the entire groove was free of debris; score 1: less than half of the groove was filled with debris; score 2: half and more than the half of the groove was filled with debris; score 3: the entire groove was filled with debris. For the statistics the Mann–Whitney *U*-test was used. The level of significance was set at p=0.05.

Results

Before the ultrasonic irrigation, the groove score was 3 for each specimen. After irrigation in group 1 there were four samples (20%) with score 1, the others (80%) had score 0: free of debris. In group 2 one sample (5%) had score 1, the others (95%) had score 0. There was no significant difference between the two groups (p=0.429).

Discussion

Because the frequency, displacement amplitude and radius of the file and the wire were the same in both groups the smooth wire was as effective as the K-file. The only difference between the two instruments is the grooving of the K-file, which is very superficial. There was no significant difference in cleaning efficacy between the smooth wire and a K-file during ultrasonic irrigation indicating that the shallow grooves of the K-file did not significantly influence the cleaning effect.

These findings correspond with Goodman et al. (1985) and Cameron (1987) who found that a smooth wire did indeed clean the root canal during ultrasonic irrigation. Ultrasonic irrigation with a smooth wire and a 2 or 4% sodium hypochlorite solution resulted in canal walls without a smear layer (Cameron 1987) and the isthmuses of the root canals contained significantly less debris after ultrasonic irrigation than the control group (Goodman et al. 1985). The studies were performed on freshly extracted teeth so the effectiveness of using a smooth wire was proven in natural teeth.

In a study where a comparison was made between a smooth wire and a size 15 K-file, during ultrasonic irrigation, less cutting of the canal wall was seen when the smooth wire was used (Mayer et al. 2002). This demonstrates the advantage of using a smooth wire to limit the cutting effect of the K-file.

In the above-mentioned studies the smooth wires were not compared with a conventional K-file or were compared with a K-file that did not have the same properties or dimensions as the K-file (Mayer et al. 2002). For this reason it was not clear if a smooth wire would be as effective in cleaning the root canal as a K-file under the same conditions.

This study was performed with straight root canals. In the study by Goodman et al. (1985) roots with a Schneider curvature between 15 and 35° were used indicating that a smooth wire is effective in both straight and curved canals.

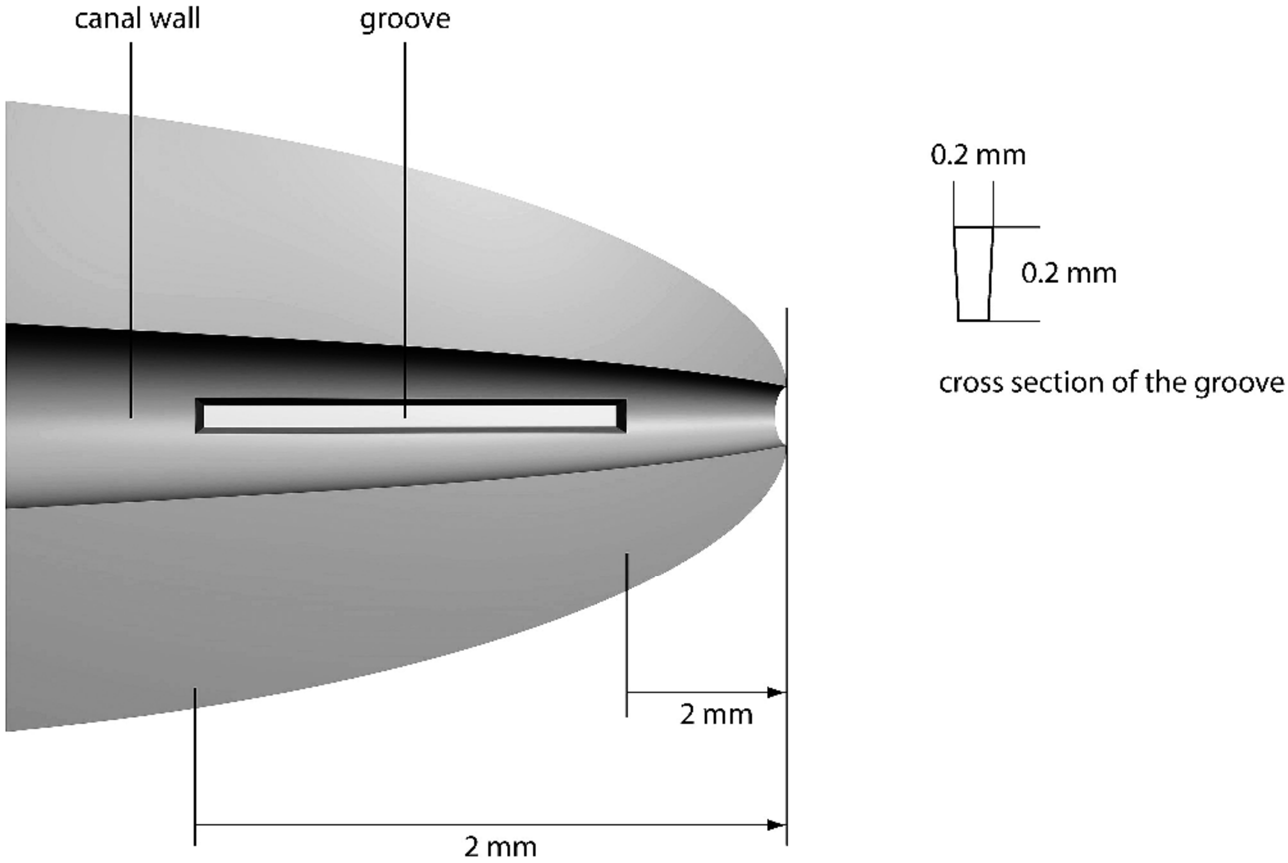
Dentine is porous, for that reason it could be more difficult to remove dentine from natural teeth than from resin blocks. This will be the same for the K-file as for the smooth wire because they create the same amount of acoustic streaming, which is responsible for the cleaning effect.

From the results of the study of Lumley et al. (1993) it can be concluded that ultrasonic irrigation is more effective when the direction of the oscillation of the file is towards the oval recesses. For this reason in this study the oscillation of the file was also towards the grooves.

Conclusion

Using a smooth wire during ultrasonic irrigation is as effective in the removal of artificially placed dentine debris in root canals in resin blocks as a size-matched conventional K-file.

Figure 1
Schematic representation of the groove model



8

The efficacy of ultrasonic irrigation to remove artificially placed dentine debris from human root canals prepared using instruments of varying taper

In International Endodontic Journal 2005; **38**, 764–768

L. W. M. van der Sluis, M-K. Wu & P. R. Wesselink

Abstract

Aim To investigate the influence of the taper of root canals on the effectiveness of ultrasonic irrigation to remove artificially placed dentine debris.
Methodology Forty-four maxillary and mandibular canines were selected after bucco-lingual and mesio-distal radiographs indicated that their internal diameters were smaller than the diameters of a size 20, .06 taper System GT instrument (Dentsply Maillefer, Ballaigues, Switzerland). These canines were divided into three groups and prepared using either size 20, .06 taper System GT instruments, size 20, .08 taper or size 20, .10 taper System GT instruments. Each root was then split longitudinally through the canal, forming two halves. In one canal wall, a standard groove was cut 2–6 mm from the apex, to simulate uninstrumented canal extensions. Each groove was filled with dentine debris mixed with 2% NaOCl to simulate a situation when dentine debris accumulates in the uninstrumented canal extensions. Each canal was reassembled by joining the two halves of the teeth by means of wires and sticky wax. In each canal ultrasonic irrigation was performed with a size 15 K file using 2% NaOCl as an irrigant. Before and after irrigation, images of each half of the canal with a groove were taken using a microscope and a digital camera, after which they were scanned into a PC as TIFF images. The quantity of dentine debris in the groove was evaluated using a scoring system: the higher the score, the larger the amount of debris. The scores before and after irrigation were compared. The differences in percentage of score reduction between the three groups were analysed by means of one-way ANOVA.
Results After ultrasonic irrigation, the debris score reduced by 74, 81 and 93%, respectively, in the size 20, .06, 20, .08 and 20, .10 taper groups. However, the difference amongst groups was not statistically significant (p=0.078).
Conclusion There was a tendency that ultrasonic irrigation was more effective in removing artificially placed dentine debris from simulated canal extensions from canals with greater tapers.

Introduction

During root canal treatment the use of sodium hypochlorite (NaOCl) as an irrigant solution is indispensable because of its tissue-dissolving capacities (Moorer & Wesselink 1982) and its antibacterial effect (Siqueira et al. 2000). The flushing action of the irrigant solution may be more important during the cleaning process than the ability of the irrigant solution to dissolve tissue (Baker et al. 1975). Most of the dentine debris is inorganic matter that cannot be dissolved by NaOCl. Therefore, removal of dentine debris relies mostly on the flushing action of irrigant.

The enhancement of the flushing action of an irrigant solution by using ultrasound is well documented (Cunningham & Martin 1982, Cunningham et al. 1982a,b, Stock 1991, Lumley et al. 1993, Lee et al. 2004a,b). Cunningham & Martin (1982) and Cunningham et al. (1982a,b) reported that more bacterial spores and dentine debris were removed during ultrasonic irrigation than hand irrigation.

However, narrow canals may compromise the efficacy of ultrasonic irrigation (Krell et al. 1988, Krell & Johnson 1988, Druttman & Stock 1989, Stock 1991). Therefore, such canals may need to be enlarged and their taper increased to allow effective ultrasonic irrigation. NiTi rotary instruments with different tapers have been used to enlarge the small root canal and are available from a variety of manufacturers. It is important to know the minimum diameter and/or taper a root canal should have to allow good ultrasonic irrigation and which diameter and/or taper restricts its effectiveness.

In a recent study (Lee et al. 2004a), simulated canals were split longitudinally, forming two halves and a standard groove was cut in one canal wall, to simulate uninstrumented canal extensions. Each groove was filled with dentine debris to simulate a situation when such debris accumulates in uninstrumented canal extensions. After reassembling the canals, ultrasonic irrigation was performed. The quantity of the debris in the groove before and after irrigation was scored and compared. It was found that after irrigation the remaining debris was significantly greater in size 20, .04 taper canals than in size 20, .06 and 20, .08 canals.

The advantage of the method used by Lee et al. (2004a,b) is that the amount of debris present both before and after irrigation could be compared, whereas in other previous studies the amount of debris was evaluated only after preparation and irrigation (Abbott et al. 1991, Lumley et al. 1993, Wu & Wesselink 1995). Because it was not clear how much debris was present before irrigation in those studies, it could not be established how much was removed using the different irrigation procedures. On the other hand, Lee et al. (2004a) conducted their experiment in simulated plastic canals; dentine, due to its porous nature (by having dentinal tubules), may act differently than a solid plastic material. Therefore, it would be interesting to repeat the same study in natural teeth to evaluate the differences between the plastic model and natural teeth.

The purpose of this study was to repeat the experiment conducted by Lee et al. (2004a) in natural teeth to investigate the influence of the taper of root canals on the effectiveness of ultrasonic irrigation to remove artificially placed dentine debris from natural root canals.

Materials and methods

Maxillary and mandibular canines were radiographed bucco-lingually and mesio-distally. The internal diameters of each root were measured on both radiographs 3, 7 and 11 mm from the apex. The diameters of a size 20, .06 rotary System GT instrument (Dentsply Maillefer, Ballaigues, Switzerland) were 0.38, 0.62 and 0.86 mm at 3, 7 and 11 mm from the tip of instrument. In 44 canines the internal diameters were smaller than the diameters of the size 20, .06 instrument at 3, 7 and 11 mm from the apex. However, it was not possible to find a canine with a single canal that was smaller than the size 20, .04 instrument.

The 44 canines were randomly divided into three groups (n = 14, 14 and 16). The canals were accessed and prepared. Each canal was prepared to the apical foramen which was determined by inserting a size 15 file into the canal until the tip of the file was just visible. The coronal aspect of each canal was flared, using Gates Glidden drills (Dentsply Maillefer); sizes 2–4 were used for the canal orifice only. The three groups were prepared using either size 20, .06 taper, size 20, .08 taper or size 20, .10 taper rotary System GT instruments (Dentsply Maillefer). Between the instruments, each canal was irrigated with 2 mL of a freshly prepared 2% solution of NaOCl, using a syringe and a 27-gauge needle that was placed 1 mm short of the working length, resulting in a total volume of 50 mL. The NaOCl solution was prepared by diluting a 10% NaOCl solution (Merck, Darmstadt, Germany). Its pH was adjusted to 10.8 with 1 N HCl. The concentration of the NaOCl solution was measured iodometrically (Moorer & Wesselink 1982).

The experiment was conducted using the methodology described by Lee et al. (2004a). Briefly, after root canal preparation each root was split longitudinally through the canal, forming two halves (Fig. 1). A standard groove of 4 mm in length, 0.2 mm in width and 0.5 mm in depth was cut in one canal wall 2–6 mm from the apex, to simulate uninstrumented canal extensions in the apical half. Each groove was filled with dentine debris mixed with 2% NaOCl to simulate a situation when dentine debris accumulates in the uninstrumented canal extensions. After reassembling the two root halves by means of wires and sticky wax, ultrasonic irrigation was performed with a piezoelectronic unit (PMax; Satelec, Meriganc, France) in each canal for 3 min using 2% NaOCl as irrigant. After switching on the ultrasound device, an activated size 15 file was placed within 1 mm of the working length, thus, oscillation of the file and irrigation began almost at the same time. The oscillation in the direction of the groove at speed 3 lasted for 3 min. According to the manufacturer, the frequency employed under these conditions was approximately 30 kHz. The root halves were separated after the irrigation procedure in order to evaluate the removal of dentine debris. Images of each halve of the canal with the groove were taken before and after irrigation, using a Photomakroskop M400 microscope with digital camera (Wild, Heerbrugg, Switzerland) at ×40 magnification; the pictures were scanned into a PC as Tagged Image File Format (TIFF) images. The quantity of the debris in the groove before and after irrigation was scored, the higher the score, the larger the amount of debris. With the scores before and after irrigation, the percentage of score reduction was calculated as follows:

$$\text{Percentage of score reduction} = \frac{\text{Score before irrigation} - \text{Score after irrigation}}{\text{Score before irrigation}} \times 100\%$$

The differences in percentage of score reduction between the three groups were analysed by means of one-way ANOVA. The level of significance was set at p=0.05.

Results

The results of the study are shown in Table 1. There was a tendency for ultrasonic irrigation to be more effective in more tapered canals, but the difference amongst the groups was not statistically significant (p=0.078).

Discussion

The results show that the ultrasonic irrigation has a tendency to remove more artificially placed dentine debris from more tapered root canals.

It has been reported that uninstrumented extensions or irregularities were totally or partially filled with debris following conventional hand irrigation (Cunningham et al. 1982a, Goodman et al. 1985, Wu & Wesselink 2001). In this study, a standard groove of 4 mm was cut, 2–6 mm from the apex and each groove was filled with dentine debris mixed with 2% NaOCl to simulate a situation where dentine debris accumulates in the uninstrumented canal extensions. This methodology has the potential to score the debris in the groove twice, and could therefore show how much debris had been removed by ultrasonic irrigation.

In a study by Albrecht et al. (2004), apical debris removal using various tapers of ProFile GT instruments (Dentsply Maillefer) was evaluated. When the taper was relatively small, significantly more debris was found when the apical preparation size was 20 compared with size 40 apical preparations. When a taper of .10 was produced, however, there was no difference in apical debris removal between apical preparations size 20 and 40. The results of the present study are in line with those results, and demonstrate a trend for better cleaning in canals prepared to a size 20, .10 taper in natural teeth (Table 1).

Because it was not possible to find canines with a canal size smaller than the System GT instrument size 20, .04, in the present study a group of teeth of that taper was not included. The 44 canals selected on the basis of the diameter on radiographs were smaller than the size 20, .06 instrument, making it possible to create three different groups consisting of sizes 20, .06, 20, .08 and 20, .10. Therefore, the present study and the study by Lee et al. (2004a) shared the 20, .06 and 20, .08 groups (Table 2).

The results of both natural and plastic root canals showed the same tendency namely that ultrasonic irrigation was more effective in removing artificially placed dentine debris from extensions in wide canals than from small canals (Table 2). However the percentage of debris score reduction was lower in natural root canals than in the corresponding-sized simulated plastic canals (Table 2), indicating that it was more difficult to remove dentine debris from natural canals than plastic canals probably due to the complicated morphology of the natural root canals and the porous dentinal wall. The data in the present study with natural root canals had a higher SD/mean ratio when compared with the data for canals in plastic blocks (Table 2), also indicating that the results of the natural root canals were influenced by the morphology of the natural root canals and the porous dentinal wall. This may partly explain why in plastic canals, the difference amongst the groups (n = 12) was significant (p=0.012) (Lee et al. 2004a,b), whereas in natural root canals the difference amongst the groups (n=14–16) was not significant (p=0.078).

Conclusion

The taper of prepared root canals influenced the effectiveness of ultrasonic irrigation in removing artificially placed dentine debris from uninstrumented canal extensions.

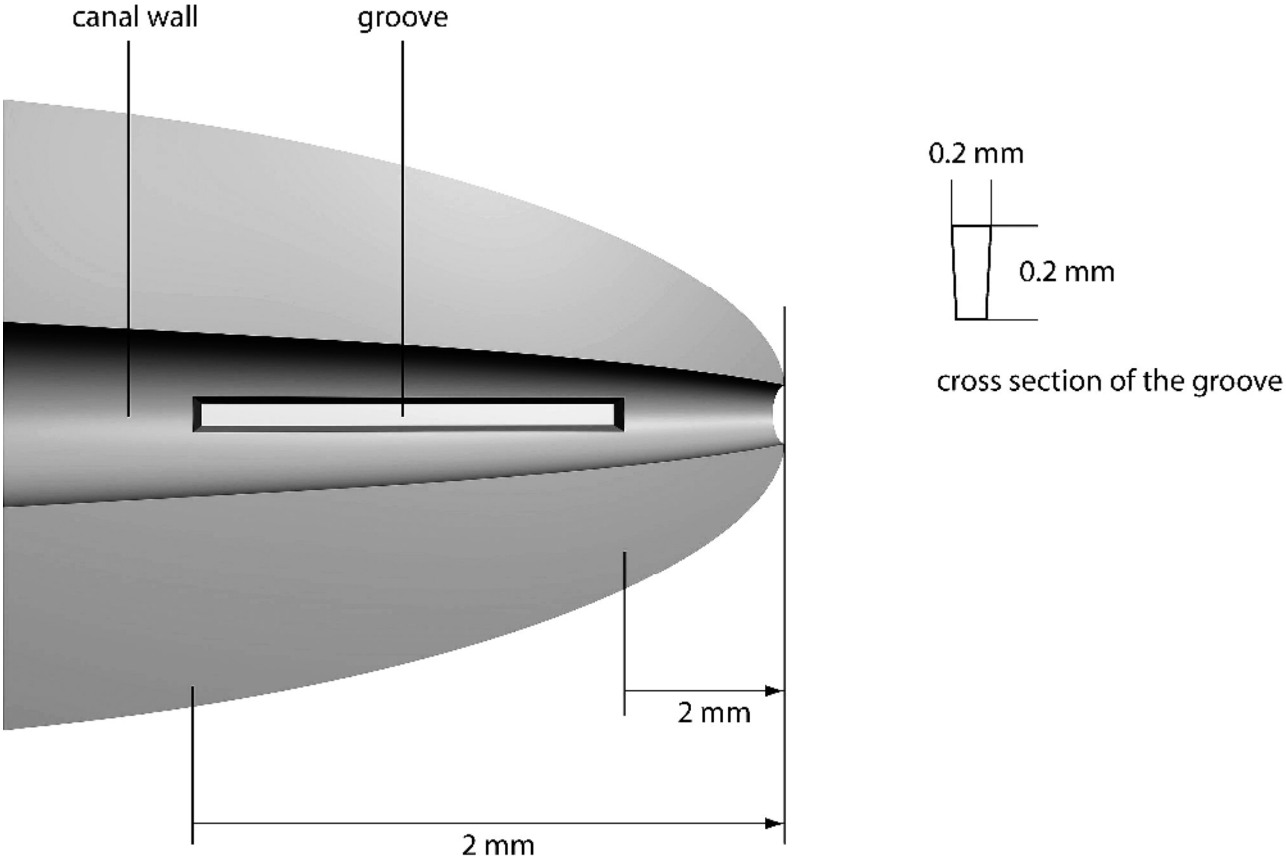
Table 1 Reduction of debris score

Size and taper of root canal	Percentage of score reduction
20, .06	73.9 ± 26.0
20, .08	80.9 ± 33.3
20, .10	92.7 ± 20.2

Table 2 Reduction of debris score after ultrasonic irrigation in different-sized root canals

Size and taper of root canal	Percentage of score reduction	
	In root canals in natural teeth (the present study)	In simulated plastic canals (Lee *et al.* 2004a)
20, .04	No data	58.3 ± 21.4
20, .06	73.9 ± 26.0	83.3 ± 26.7
20, .08	80.9 ± 33.3	94.4 ± 13.0
20, .10	92.7 ± 20.2	No data

Figure 1
Schematic representation of the groove model



9

The influence of volume, type of irrigant and flushing method on removing artificially placed dentine debris from the apical root canal during passive ultrasonic irrigation

In International Endodontic Journal 2006; **39**, 472-6
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Abstract

Aim To determine the influence of volume, irrigant and method of flushing on the removal of artificiallyplaced dentine debris from the apical part of root canals during passive ultrasonic irrigation.

Methodology Access cavities were prepared in 15 canine teeth and their root canals instrumented to size 20, 0.10 taper. Each root was split longitudinally, forming two halves. A groove was cut in the canal wall 2–6 mm from the apex in each half which was then filled with dentine debris prior to the roots being reassembled. All canals were ultrasonically irrigated, using a size 15, 0.02 taper smooth wire to a length of 21 mm that was placed in the canal to the apical foramen. In group 1 the canal was flushed with a continuous flow of 50 mL 2% sodium hypochlorite (NaOCl). In group 2 the continuous flow was not used but the canal was flushed with 12 mL 2% NaOCl, at a rate of 2 mL 30 s^{-1} using a syringe. Group 3 was treated in the same way as group 2 but the canal was flushed with 6 mL 2% NaOCl, at a rate of 2 mL min^{-1}. Group 4 was treated in the same way as group 1 but water was used as the irrigant. Before and after irrigation, images of the grooves were captured and stored. The quantity of dentine debris in the groove was evaluated. The differences in debris scores between the experimental groups were analysed with the Kruskal–Wallis test and the Mann–Whitney U-test. The level of significance was set at $p=0.05$.

Results The difference between all groups was statistically significant (K–W test $p<0.001$).Groups 1, 2 and 3 differed significantly from group 4 ($p<0.001$); there was no significant difference between groups 1, 2 and 3 ($p\leq 0.550$).

Conclusions Syringe delivery of 2% NaOCl (6 and 12 mL) was as effective as a continuous flow of 2% NaOCl (50 mL). Water was not effective in removing dentine debris from grooves in the apical portion of root canals.

Introduction

It has been established that passive ultrasonic irrigation in combination with sodium hypochlorite (NaOCl) is more effective than conventional hand irrigation in removing dentine debris from the root canal (Goodman et al. 1985, Lee et al. 2004b). Other studies have shown that water is ineffective in removing dentine debris from the root canal during passive ultrasonic irrigation (Cameron 1987, Cheung & Stock 1993, Guerisoli et al. 2002). However, a controlled quantitative comparative study of the capacity to remove dentine debris from the root canal between water and NaOCl has never been performed.

Passive ultrasonic irrigation is the most efficient method of ultrasonic irrigation (Ahmad et al. 1987b). Passive ultrasonic irrigation implies that it will be performed following root canal preparation, irrespective of the preparation method used, up to the size of the master apical file. In this way the ultrasonic file can oscillate freely in the root canal and its cutting action reduced to a minimum. When the file oscillates freely, acoustic streaming and/or cavitation is more powerful (Roy et al. 1994).

Chlorine is responsible for the dissolution of organic tissue and the antimicrobial effect of NaOCl (Moorer & Wesselink 1982). However, chlorine is consumed rapidly during the first phase of tissue dissolution, probably within 2 min (Moorer & Wesselink 1982). Therefore regular replenishment and large volumes of NaOCl are required. However, it has not been determined how large the volume of NaOCl should be during passive ultrasonic irrigation.

With certain ultrasonic devices it is possible to use a continuous flow of irrigant during ultrasonic irrigation (Lee et al. 2004b). It is also possible to place NaOCl into the canal with a syringe and then activate the ultrasonic file (Cameron 1987). It is not known whether during ultrasonic irrigation a continuous flow of irrigant is more or less efficient in the removal of dentine debris from the root canal than syringe delivery of the irrigant. Syringe delivery of the irrigant allows full control of the procedure because the depth of needle penetration in the canal and the volume flushed through the canal are known. When using a continuous flow of irrigant, the volume through the root canal is not controlled as it is not measured or standardized.

The purpose of this study was to evaluate the effect of the volume, type of irrigant and the method of flushing the root canal on the removal of dentine debris from artificial extensions of the apical root canal during ultrasonic irrigation.

Materials and methods

Fifteen maxillary and mandibular canines were selected after bucco-lingual and mesio-distal radiographs indicated that their internal diameters at three points (3, 5 and 8 mm from the apex) were smaller than the corresponding diameters of a size 20, 0.10 taper GT instrument (Dentsply Maillefer, Ballaigues, Switzerland). Access cavities were prepared and the root canals shaped. Each canal was prepared to the apical foramen which was determined by inserting a size 15 K-file into the canal until the tip of the file was just visible. The coronal aspect of each canal was flared, using sizes 2–4 Gates Glidden drills (Dentsply Maillefer, Ballaigues, Switzerland); in the canal orifice only. The root canals were prepared to a size 20, 0.10 GT instrument. Between each instrument, the canals were irrigated with 2 mL of a freshly prepared 2% solution of NaOCl, using a syringe and a 27-gauge needle that was placed 1 mm short of the working length, resulting in a total volume of 30 mL. The NaOCl solution was prepared by diluting a 10% NaOCl solution (Merck, Darmstadt, Germany). Its pH

was adjusted to 10.8 with 1 N HCl. The concentration of the NaOCl solution was measured iodometrically (Moorer & Wesselink 1982).
After root canal preparation each root was split longitudinally through the canal, forming two halves. A standard groove of 4 mm in length, 0.2 mm in width and 0.5 mm in depth was cut in one canal wall 2– 6 mm from the apex (Fig. 1), to simulate uninstrumented canal extensions in the apical half (Lee et al. 2004a). Each groove was filled with dentine debris mixed with 2% NaOCl to simulate a situation when dentine debris accumulates in natural uninstrumented canal extensions. The amount of dentine debris and NaOCl and the time of application between mixing and placement were standardized. Images of each half of the canal with a groove were taken using a digital camera Konica Minolta Dimage Z10 (Konica Minolta, Mah Wah, NJ, USA), after which the images were loaded on a laptop, Asus M6 Boone (Dell Inc., USA), as jpg images with a USB cable. After reassembling the two root halves by means of wires and sticky wax, ultrasonic irrigation was performed with a piezoelectronic unit (PMax: Satelec, Meriganc, France).

Four experiments were performed with the 15 teeth after a pilot study demonstrated that the smooth wire did not damage the root dentine or alter the form of the groove. In group 1 (n = 15) the root canals were ultrasonically irrigated for 3 min with a continuous flow of 50 mL 2% NaOCl. Group 2 (n = 15) was the same as group 1 with the exception that a continuous flow of irrigant was not used, rather the canal was flushed every 30 s with 2 mL 2% NaOCl using a syringe (total volume 12 mL). Group 3 (n = 15) was the same as group 2 with the exception that the canal was flushed every minute (total volume 6 mL). Group 4 (n = 15) was the same as group 1 with the exception that water was used as irrigant. After switching on the ultrasonic device, an activated 21 mm long stainless steel smooth wire with a 0.15 mm diameter and 0.02 taper (van der Sluis et al. 2005a) was placed in the canal as far as the apical foramen, the oscillation of the wire and irrigation began almost at the same time when the continuous flow was used. When no continuous flow was used, NaOCl was administered into the root canal by a syringe before inserting the ultrasonically activated wire. The oscillation of the wire was directed towards the groove and the intensity was set on speed 'blue 4'. In accordance with the manufacturer's, instructions the frequency employed under these conditions was approximately 30 kHz and the displacement-amplitude varied between 20 and 30 μm.

The root halves were separated after the irrigation procedure in order to evaluate the removal of dentine debris. After irrigation, images of each half of the canal with a groove were taken using a digital camera Konica Minolta Dimage Z10, after which the images were loaded on a laptop, Asus M6 Boone, as jpg images with a USB cable. No extra magnification except for the magnification of the digital camera was necessary for the quanitification of the dentine debris. The quantity of the debris in the groove before and after irrigation was scored independently by three calibrated dentists using the following scores: 0, the groove is empty; 1, less than half of the groove is filled with debris; 2, more than half of the groove is filled with debris; 3, the groove is filled completely with debris. With the scores before and after irrigation, the percentage of score reduction was calculated as follows:

$$\text{Percentage of score reduction} = \frac{\text{Score before irrigation - Score after irrigation}}{\text{Score before irrigation}} \times 100\%$$

The differences in debris scores between the different groups were analysed by means of Kruskal–Wallis test and the Mann–Whitney U-test. The level of significance was set at $p \leq 0.05$.

Results

The results of the study are shown in Table 1. The difference between all groups was statistically significant (K–W test $p<0.001$). Groups 1, 2 and 3 differed significantly from group 4 ($p<0.001$), but there was no significant difference ($p=0.550$) between groups 1, 2 and 3.

Discussion

In a recent study (van der Sluis et al. 2005b) dentine debris removal from artificial extensions in the apical root canal was studied in canals of size 20, 0.06 taper, a taper 0.08 or a taper 0.1. The canals of size 20 and 0.1 taper had the greatest percentage of dentine debris removal (92.7%). Therefore, canals of size 20, 0.1 taper were used in this study.

It has been reported that uninstrumented extensions or irregularities in root canals were totally or partially filled with dentine debris following conventional hand irrigation (Goodman et al. 1985, Wu & Wesselink 2001). In the present study, a standard 4 mm groove was prepared, 2–6 mm from the apex and each groove was filled with dentine debris mixed with 2% NaOCl to simulate a situation where dentine debris accumulates in uninstrumented oval canal extensions. This methodology has the potential to score the dentine debris in the groove before and after the treatment and thus shows how much dentine debris had been removed by ultrasonic irrigation (Lee et al. 2004a,b, van der Sluis et al. 2005a).

From the results of this study it can be concluded that water as an irrigant during ultrasonic irrigation is not as effective as 2%NaOCl in removing dentine debris from extensions in the apical root canal. This confirms the results of other studies (Cameron 1987, Cheung & Stock 1993, Guerisoli et al. 2002). However, explanations for this enhanced cleaning effect are a matter of debate.

The significantly increased capacity of NaOCl to dissolve organic material when it is agitated by ultrasound (Moorer & Wesselink 1982) or when the temperature rises because of ultrasound energy (Cunningham & Balekjian 1980, Ahmad 1990) could explain the results. During ultrasonic irrigation different processes can occur when NaOCl is used as irrigant. For example, the ‘boiling point’ of NaOCl is 40 C˚, at which point the NaOCl will decompose. NaOCl can decompose and partially split into the sodium cation ($Na+$), hypochlorite anion ($ClO)$), sodium hydroxide ($NaOH$), hypochlorous acid ($ClOH$), chlorine (Cl_2), oxygen (O) or sodium chlorate ($NaCl$). During cavitation oscillating bubbles will form in the irrigant that will contain dissolved gas. When the bubble is in the expansion phase, gas will diffuse into the bubble; conversely, when the bubble is in the compression phase, gas will diffuse out of the bubble (Crum 1994). Chlorine could have an influence on this process by diffusing in the bubble. Bubbles can transport gas during cavitation (Leighton 1994). This could have an effect on the spread of chlorine through the irrigant. Bubbles formed in salt water tend to be more numerous, especially the smallest bubbles, and less prone to coalesce than bubbles in fresh water (Leighton 1994). These detailed factors could explain the difference in the action of water and NaOCl as irrigants. However, further research is required to explain the mechanism more clearly.

From the results it can be concluded that syringe delivery of irrigant during ultrasonic irrigation is as effective as a continuous flow of irrigant in the removal of dentine debris from extensions in the apical root canal. The maximum volume during 3 min of ultrasonic irrigation with the device employed in this study was 200 mL. A pilot study demonstrated that 50 mL during 3 min of irrigation (the minimum volume when continuous flow is possible) was as effective in dentine debris removal from an oval root canal as 200 mL. The results from the pilot study and the main study show that a continuous flow of 50 mL during 3 min of ultrasonic irrigation was sufficient to result in effective dentine debris removal from grooves cut in the wall of an oval root canal. It is not known if even less volume of irrigant during a continuous flow will result inefficient dentine debris removal. During syringe delivery of the irrigant, the penetration depth of the needle and the volume that flows through the apical root canal are known. It is not possible to standardize the amount of NaOCl, which flows through the root canal during a continuous flow of irrigant because it is not known how much irrigant actually enters the root canal and flows through the apical part. During the procedure too many variables are involved which are impossible to standardize because the irrigant is always delivered outside the root canal. These variables include the placement of the suction tube, the width of the irrigant jet and the location and dimension of the root canal orifice.

From the results of this study it can also be concluded that 2 mL of 2% NaOCl delivered every minute by a syringe is as effective as 2 mL of 2% NaOCl delivered every 30 s during 3 min of ultrasonic irrigation in the removal of dentine debris from extensions in the apical root canal. When 2% NaOCl is refreshed every minute it is possible that sufficient free chlorine is present in the root canal to dissolve the organic component of dentine debris. In addition, the flushing effect seems adequate in the removal of inorganic dentine debris from the root canal when it is introduced ultrasonically every minute with 2 mL 2% NaOCl. It is not known if no refreshment of NaOCl during ultrasonic irrigation results in adequate dentine debris removal. It could be possible that 2 mL of 2% NaOCl contains enough free chlorine to dissolve the organic component of the dentine debris and that one refreshment of NaOCl has enough flushing effect to remove the inorganic component of dentine debris. This should be studied further.

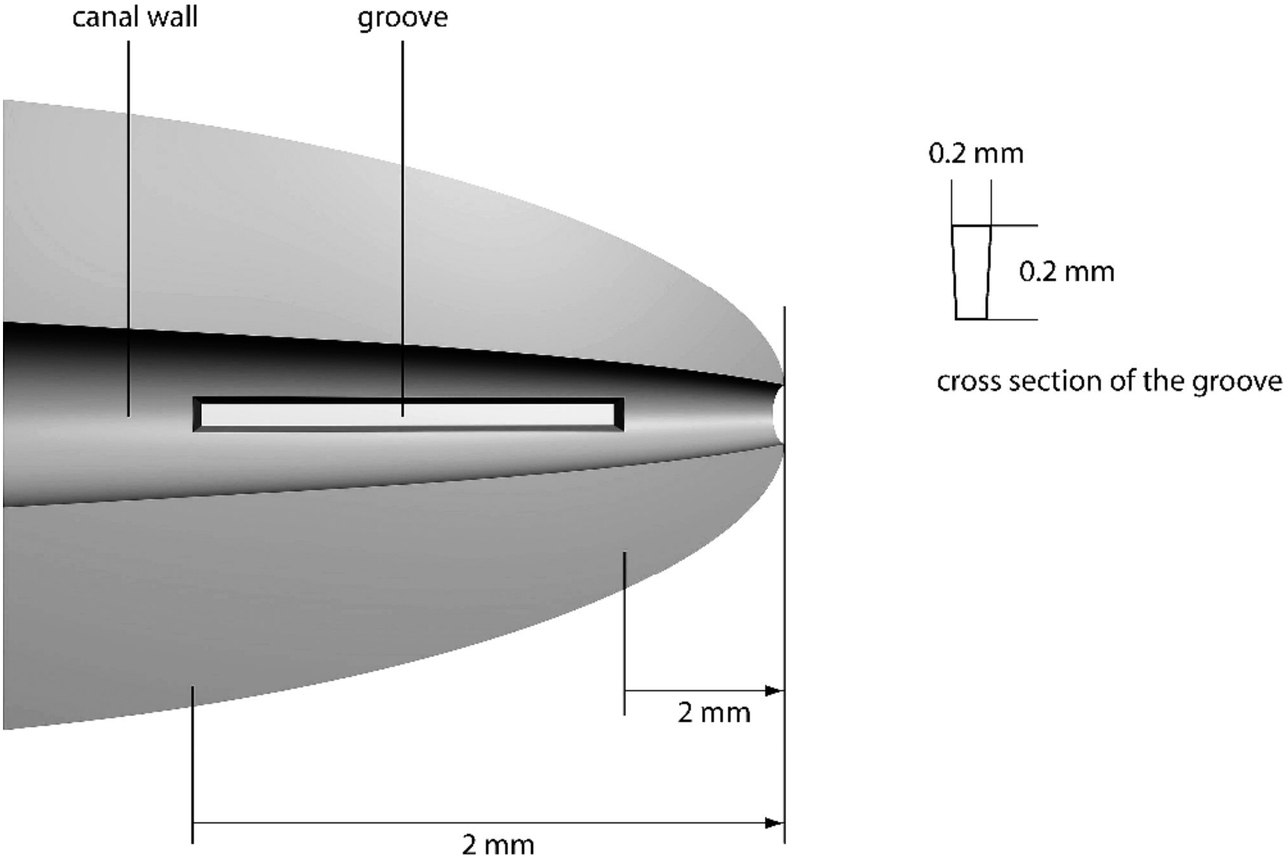
Conclusion

Syringe delivery of 2% NaOCl (6 and 12 mL) was as effective as a continuous flow of 2% NaOCl (50 mL) during passive ultrasonic irrigation in removing dentine debris from artificial extensions in the apical root canal. Water, as irrigant during passive ultrasonic irrigation, was not effective in removing dentine debris from the apical root canal.

Table 1 Score of dentine debris before and after ultrasonic irrigation and the percentage of score reduction

groups	before	after		percentage of score reduction
		mean	SD	
group:1	3.00	0.07	0.26	98%
group:2	3.00	0.07	0.26	98%
group:3	3.00	0.13	0.35	96%
group:4	3.00	1.67	1.11	44%

Figure 1
Schematic representation of the groove model



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A comparison of two different flushing methods used in passive ultrasonic irrigation.

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Abstract

Aim To compare the effectiveness of two different flushing methods in passive ultrasonic irrigation.

Methodology Fifteen models of root canals instrumented to size 20, taper 0.10 were used. Each root was split longitudinally, forming two halves. A groove was cut in the canal wall 2-6 mm from the apex in each half which was then filled with dentine debris prior to the roots being reassembled. All canals were ultrasonically irrigated. Before and after irrigation, images of the grooves were captured and stored. The quantity of dentine debris was evaluated. In group 1 and 2 (n=15) the canal was flushed 1.5 or 3 minutes with a continuous flow of 15 $mLmin^{-1}$ 2% NaOCl (continuous flushing). In groups 3 and 4 (n=15) the canal was flushed intermittently for 1 or 3 minutes (intermittent flushing). Group 5 (n=15) was the same as groups 1 but with water as the irrigant. The differences in debris score between the experimental groups were analysed with the Kruskall-Wallis test and the Mann-Whitney *U*-test. The level of significance was set at $p \leq 0.05$.

Results The debris score was reduced by 97% or 98% in the two intermittent flushing groups and the 3 minutes continuous flushing group ($p>0.05$).

Conclusion PUI with either 1- or 3 minutes intermittent flushing of 2% NaOCl is as effective as PUI with 3 minutes of continuous flushing 2% NaOCl in removing debris from the root canal.

Introduction

The goal of irrigation of the root canal is to remove tissue and or microorganisms (planktonic or biofilm) from the root canal system (Haapasalo et al. 2005). When the root canal is instrumented before irrigation, irrigation should also remove smear layer and dentine debris, side effects of instrumentation of the root canal (Baugh et al. 2005). The efficacy of the irrigation depends strongly on the working mechanisms of the irrigant and the ability to bring the irrigant in contact with the structures, which have to be removed from the root canal (Chow et al. 1983, Rosenfeld et al. 1978). Sodium hypochlorite (NaOCl) is widely used as an endodontic disinfectants and is effective because it is a strong dissolver of organic tissue, antibacterial, acts as a lubricant and is non toxic (Haapasalo et al. 2005). However, chlorine, which is responsible for the dissolving and antibacterial capacity of NaOCl, is very unstable and is consumed rapidly during the first phase of tissue dissolution, probably within 2 min (Moorer & Wesselink 1982). Therefore refreshment of the irrigant is a very important part of irrigation.

During ultrasonic root canal preparation it is impossible to control the cutting of dentine and therefore it is difficult to control the shape of the prepared root canal. This could result in apical perforation and an irregular shape of the root canal (Stock 1991, Lumley et al. 1992). Passive ultrasonic irrigation (PUI) does not have these disadvantages because during PUI the file does not instrument the root canal wall. During PUI an ultrasonically oscillating small file or smooth wire (e.g. size:15, 20)(van der Sluis et al. 2005) is placed in the centre of the root canal, after the root canal has been shaped up to the master apical file (Ahmad et al. 1987). Because the root canal has been enlarged, the irrigant can flow in the root canal and the file or wire can vibrate relatively free, which will result in a more powerful acoustic streaming (Ahmad et al. 1987). However the use of a file or wire does not aim to shape the root canal wall. PUI with sodium hypochlorite (NaOCl) as irrigant, removes more dentine debris, planktonic bacteria and pulp tissue from the root canal than syringe irrigation (Huque et al. 1998, Lee et al. 2004, Gutarts et al. 2005).

Two flushing methods can be used during PUI namely a continuous flush of irrigant from the ultrasonic handpiece or an intermittent flushing method using a syringe (Cameron 1988). During the intermittent flushing method, the irrigant is injected into the root canal by a syringe, and refreshed several times after each ultrasonic activation. During ultrasonic activation, an ultrasonically oscillating instrument (file or smooth wire) will activate a streaming of the irrigant in the root canal during which micro-organism, dentine debris or organic tissue can be detached from the root canal wall and will be absorbed or dissolved in the irrigant (Weller et al. 1980, Moorer & Wesselink 1982). Hereafter the root canal is flushed with 2 mL of fresh irrigant to remove the remnants from the root canal. If the both system are equally effective in refreshment of the irrigant is unknown.

The influence of irrigation time on the efficacy of PUI is at present not clear. One study claims an increased removal of the smear layer after 5 minutes of PUI as opposed to 3 minutes (Cameron 1983). In the study of Sabins et al. (2003) no significant difference in dentine debris removal was found between 30 and 60 seconds of PUI. In both studies the NaOCl was injected into the root canal by a syringe. In the study of Cameron (1983) however, the NaOCl was refreshed every minute (intermittent flush technique), in the study of Sabins et al. (2003) the NaOCl was not refreshed. Perhaps the contrasting results of these studies could be explained by the absent refreshment of irrigant in the study of Sabins et al. (2003).

The purpose of this study was to compare the effectiveness of two different flushing methods in passive ultrasonic irrigation.

Materials and methods

Fifteen maxillary and mandibular canines were selected after bucco-lingual and mesio-distal radiographs indicated that their internal diameters at three points (3, 5 and 8 mm from the apex) were smaller than the corresponding diameters of a size 20, 0.10 taper GT instrument (Dentsply Maillefer, Ballaigues, Switserland). Access cavities were prepared and the root canals shaped. Each canal was prepared to the apical foramen which was determined by inserting a size 15 K-file into the canal until the tip of the file was just visible. The canal orifice of each canal was flared, using sizes 2-4 Gates Glidden drills (Dentsply Maillefer). The root canals were prepared until size 20, 0.10 GT instrument that was the largest file used. Between each instrument, the canals were irrigated with 2 mL of a freshly prepared 2% solution of sodium hypochlorite (NaOCl), using a syringe and a 30-gauge needle that was placed 1 mm short of the working length, resulting in a total volume of 30 mL. The NaOCl solution was prepared by diluting a 10% NaOCl solution (Merck, Darmstadt, Germany). Its pH was adjusted to 10.8 with 1 N HCl. The concentration of the NaOCl solution was measured iodometrically (Moorer & Wesselink 1982).

After root canal preparation each root was split longitudinally through the canal, forming two halves. A standard groove of 4 mm in length, 0.2 mm in width and 0.5 mm in depth was cut in one canal wall 2 to 6 mm from the apex, to simulate uninstrumented canal extensions in the apical half (Lee et al. 2004a) (Fig. 1). Each groove was filled with dentine debris mixed with 2% NaOCl to simulate a situation when dentine debris accumulates in the uninstrumented canal extensions. The amount of dentine debris and NaOCl and the time of application between mixing and placement were standardized. Images of each half of the canal with a groove were taken using a Photomakroskop M 400 microscope with a digital camera (Wild, Heerbrugg, Switzerland) at x 40 magnification; the photos were then scanned as tagged-image file format images. After reassembling the two root halves by means of wires and sticky wax, ultrasonic irrigation was performed with a piezoelectronic unit (PMax: Satelec, Meriganc, France).

Five experiments were performed with the fifteen models after a pilot study demonstrated that the smooth wire did not damage the root dentine or alter the form of the groove (van der Sluis et al. 2005). In group 1 (n=15) the root canals were ultrasonically irrigated for 3 minutes with a continuous flush of 15 $mLmin^{-1}$ 2% NaOCl (van der Sluis et al. 2006). Group 2 (n=15) was the same as group 1 only the irrigation time was set at 1.5 minute. In group 3 (n=15) the irrigant in the root canals was ultrasonically activated for 3 minutes and refreshed following the intermittent flushing method. The root canal was flushed every minute with 2 mL 2%NaOCl using a syringe and a 27-gauge needle that was placed 1 mm short of the working length. The total volume was 6 mL. Group 4 (n=15) is the same as group 3 with the exception that the total irrigation time was 1 minute and the canal was flushed every 20 seconds with 2 ml 2% NaOCl. Group 5 (n=15) was the same as group 1 only with water as irrigant.

After switching on the ultrasonic device, an activated 21 mm long stainless steel smooth wire with a 0.15 mm diameter and 0.02 taper (van der Sluis *et al.* 2005) was placed in the canal as far as the apical foramen, the oscillation of the wire and irrigation began almost at the same time when the continuous flow was used. When no continuous flow was used, NaOCl was administered into the root canal by a syringe before inserting the ultrasonically activated wire. The oscillation of the wire was directed towards the groove and the intensity was set on speed 'blue 4'. According to the manufacturer, the frequency used under these conditions was approximately 30 kHz and the displacement amplitude varied between 20 and 30 µm. The root halves were separated after the irrigation procedure in order to evaluate the removal of dentine debris. After irrigation, images of each half of the canal with a groove were taken using Photomakroskop M 400 microscope with a digital camera (Wild, Heerbrugg, Switzerland) at x 40 magnification; the photos were then scanned as tagged-image file format images.

The quantity of the debris in the groove before and after irrigation was scored independently by three calibrated dentists using the following scores, score: 0 the groove is empty, score:1 less than half of the groove is filled with debris, score: 2 more than half of the groove is filled with debris, score: 3 the complete groove is filled with debris. The difference in the scoring between the three dentists should be less than 5%. With the scores before and after irrigation, the percentage of score reduction was calculated as follows:

$$\text{Percentage of score reduction} = \frac{\text{Score before irrigation - Score after irrigation}}{\text{Score before irrigation}} \times 100\%$$

The differences in debris scores between the different groups were analyzed by means of the Kruskal-Wallis test and the Mann-Whitney test. The level of significance was set at p= 0.05.

Results

The scores are presented in Table: 1. There was a significant difference between the five groups (Kruskal-Wallis Test p=0.0001). In group 1 to 4, with 2% NaOCl as irrigant, significantly more dentine debris was removed from the root canal than in group 5 where water was used as irrigant. The removal of dentine debris in group 1, 3 and 4 was not significantly different (p>0.05), the debris score was reduced by 97% or 98% (Table 1). Group 1 and 4 removed significantly more dentine debris than in group 2 (Mann-Whitney Test p=0.03), the difference between group 2 and 3 was almost significant (p=0.077).

Discussion

Both flushing methods removed almost 98% of dentine debris from the apical root canal in an in vitro study when the irrigation time was set at three minutes (van der Sluis et al. 2006).

The results of this study demonstrate that when the intermittent flushing method is used, 1 minute PUI is as effective as 3 minutes in removing dentine debris from the apical root canal. When a continuous flush of irrigant is used for 1.5 minutes, PUI is less effective than 3 minutes. One minute PUI with the intermittent flushing method is as effective as 3 minutes PUI with a continuous flush.

The results of PUI with a continuous flush confirm the finding of Druttman & Stock (1989), Krell et al.(1988) and Passarinho-Neto et al. (2006) that the penetration of irrigant in the root canal, using a continuous flush, depends on the irrigation time. The longer the irrigation time the deeper the penetration of the irrigant in the root canal and the more the apical refreshment of the irrigant. In the study of Passarinho-Neto et al. (2006) more dentine debris could be removed from the root canal after 5 minutes than 1 minute of PUI combined with the continuous flush of irrigant using a standardised volume of irrigant. During PUI with a continuous flush, the irrigant flows in the pulp chamber of the tooth. The irrigant has to be transported from the pulp chamber to the apical part of the root canal by the streaming of the irrigant induced by the ultrasonically activated file.

In group 2 the irrigation time was reduced from 3 minutes to 1.5 minutes and consequently also the volume of irrigant was reduced from 45 to 22.5 mL. This could have an influence on the outcome of the study. However 22.5 mL already results in a surplus of irrigant in the pulp chamber because an average pulp chamber can only contain 0.1 mL of irrigant. The bottleneck seems to be the flow from the pulp chamber to the apical root canal and not the amount of irrigant flowing from the ultrasonic handpiece to the pulp chamber.

No detailed information is available on the properties of the apical flow during PUI. Because the displacement amplitude of the ultrasonically activated file is the largest at the tip of the file, a stream could occur from the apical to the coronal and vice versa (Ahmad et al. 1987). To which extend this occurs is not known. Krell et al. (1988) found that the possibility of the file to move freely in the root canal has a positive influence on the penetration of irrigant in the root canal. The dimension of the root canal had to be larger than the file used, therefore the smaller the file used the smaller the dimension of the root canal necessary for a desirable penetration (irrigation) effect. In this study a small wire (size 15 taper 0.02) was used. Further research is needed to clarify the streaming of irrigant during PUI and its effect on the cleaning efficacy.

As a consequence of the above mentioned facts the apical flow and the refreshment of irrigant can not be controlled when the continuous flush method is used. The advantage of the intermittent flushing method is the more efficient control of the refreshment of irrigant because the depth of the needle insertion (in this study 1 mm coronal of the working length) and the volume are known. Irrigation is more effective when the irrigant is in close relation to the tissue or debris which has to be removed from the root canal (Chow et al. 1983, Rosenfeld et al. 1978).

During the intermittent flushing method the irrigation process consists of two components namely the flushing and the ultrasonically activation of the irrigant. Sabins et al. (2003) reported no significant difference in dentine debris removal between 30 or 60 seconds of ultrasonically activation when the irrigant was not refreshed. Probably an ultrasonic activation longer than 30 seconds does not increase its efficacy. The results confirm the findings of Sabins et al. (2003) because no significant difference was found between 1 minute and 20 seconds of ultrasonic activation. For the efficacy of NaOCl as endodontic irrigant, refreshment is important because chlorine is very unstable (Moorer & Wesselink 1982). Chlorine dissolves organic material, is antibacterial and could play a role in the activity of the acoustic streaming (Moorer & Wesselink 1982, van der Sluis et al. 2007).

The continuous flush of irrigant cools the irrigant in the coronal root canal because the pulp chamber is constantly supplied with fresh cool irrigant (Cameron 1988). During the intermittent flush method, the coronal part is not cooled and thus the irrigant in the root canal will be heated due to the energy of the ultrasonic irrigation (Cameron 1988, Ahmad 1990). Cameron 1988 reported a heating of the intracanal temperature from 37°C to 45°C near by the tip of the instrument and 37 °C away from the tip during 30 seconds of ultrasonic activation of the irrigant without refreshment. A cooling effect from 37°C to 29°C was recorded during the continuous flush method.

The temperature of the irrigant was 25°C. Before irrigation the internal and external temperature of the root was stabilized at 37 °C. The external temperature stabilized at 32°C during the continuous flush method and reached a maximum of 40°C during the intermittent flush method. Ahmad 1990 reported a mean rise of temperature of 0.6°C during a continuous flow. The initial temperature of the irrigant was 20°C. The heating of NaOCl could enhance the organic tissue dissolving capacity and could influence the oscillation of cavitation bubbles of the irrigant (van der Sluis et al. 2007).

Group 3 did not remove significant more dentine debris from the groove than group 2. However the p value was 0.077 which is almost significant. Considering the modest sample size (n =15), it is difficult to accept the null hypothesis (Ho), under which the debris score for group 3 did not differ from that for group 2.

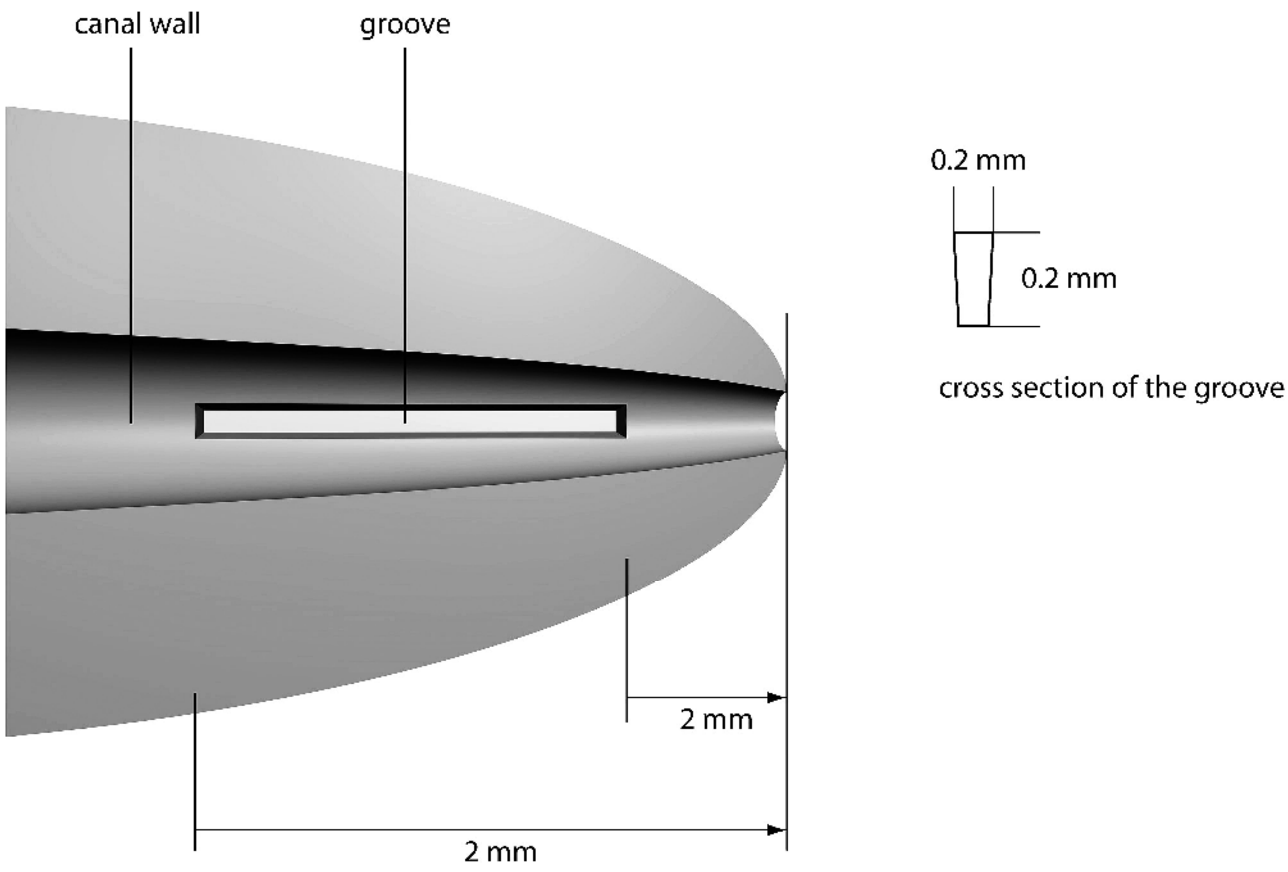
Conclusion

One minute of PUI combined with the intermittent flush method is as effective as 3 minutes of PUI with a continuous flush of 2% NaOCl. One and a half minute of PUI with a continuous flush is less effective than 3 minutes.

Table 1 Mean ± SD of dentine debris score in the groove and the percentage of score reduction of the continuous flush - and the intermittent flushing method.

flushing method	irrigant	N	Mean	SD	% score reduction
continuous 3 min.	2%NaOCl	15	0.07	0.3	98%
continuous 1.5 min.	2%NaOCl	15	0.6	0.8	80%
intermittent 3 min.	2%NaOCl	15	0.1	0.4	97%
intermittent 1 min.	2%NaOCl	15	0.07	0.3	98%
continuous 3 min	water	15	1.7	1.1	43%

Figure 1
Schematic representation of the groove model



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The evaluation of removal of $Ca(OH)_2$ from an artificial standardized groove in the apical root canal using different irrigation methodologies

In International Endodontic Journal 2007; **40**, 52-7
L.W.M. van der Sluis, M.K. Wu and P. R. Wesselink

Abstract

Aim To evaluate the capacity to remove $Ca(OH)_2$ from the root canal and to make an evaluation of the efficacy of $Ca(OH)_2$ removal during passive ultrasonic irrigation (PUI) between NaOCl and water as irrigant.
Methodology Sixteen mandibular premolars were used. Each root was prepared until the apical foramen using GT instruments, file size 30, 0.06 taper. Each root was split longitudinally. In one half of the root, a groove was cut in the canal wall 2 to 6 mm from the apex which was then filled with $Ca(OH)_2$. Subsequently the roots were reassembled. In group 1 (n=16) the teeth were ultrasonically irrigated using 50 mL 2.0% NaOCl as the irrigant. Group 2 (n=16) was the same as 1 but 50 mL 2.0% NaOCl was replaced by water. In group 3 (n=16) the teeth were irrigated by syringe injection of 50 mL 2.0%NaOCl. The quantity of remaining $Ca(OH)_2$ in the groove was scored and the data were analyzed with the Kruskal-Wallis test and the Mann-Whitney test.
Results The difference in remaining $Ca(OH)_2$ between all groups was statistically significant ($p<0.001$). Group: 1 had significantly lower scores than group 2 ($p<0.001$) and 3 ($p=0.002$) but there was no significant difference between group 2 and 3 ($p=0.765$).
Conclusions PUI with 2 % NaOCl is more effective in removing $Ca(OH)_2$ from the root canal than syringe delivery of 2% NaOCl or water as irrigant during PUI.

Introduction

Calcium hydroxide ($Ca(OH)_2$) in a non setting paste form is used widely as an intracanal medicament during root canal treatment because of its antimicrobial properties (Siqueira & Lopes 1999, Law & Messer 2004). The most frequently described method for removal of $Ca(OH)_2$ from the root canal is instrumentation of the root canal withthe master apical file in combination with copious irrigation of NaOCl and EDTA (Lambriandis et al. 2006). EDTA has the ability to neutralize $Ca(OH)_2$ residues, which could prevent a chemical reaction with the sealer, or chelate $Ca(OH)_2$ residues, which could make them easier to remove by irrigation (Margelos et al. 1997). However, it has been reported that removal of $Ca(OH)_2$ from the apical root canal wall when this method is used is difficult (Margelos et al. 1997, Lambriandis et al. 1999, 2006). This can be explained because instrumentation and irrigation alone cannot completely clean the entire root canal wall (Wu et al. 2003). When $Ca(OH)_2$ isremoved from the main canal with a file, remnants will remain in canal extensions or irregularities. From these canal extensions or irregularities it is only possible to remove the $Ca(OH)_2$ by irrigation. Passive ultrasonic irrigation (PUI) is more effective in dentine debris removal from the root canal wall than syringe delivery of the irrigant (Goodman et al. 1985, Lee et al. 2004b). However, whether PUI can remove $Ca(OH)_2$ from the root canal wall is not known.

PUI is based on the transmission of energy from an ultrasonically oscillating instrument to the irrigant in the root canal (van der Sluis et al. 2005a). In the irrigant solution, acoustic streaming and/or cavitation will occur thatis more powerful when the root canal wall is not touched deliberately with the oscillating instrument (Ahmad et al. 1988, Roy et al. 1994). Therefore, PUI is undertaken after the root canal is prepared up tothe master apical file and without instrumenting the root canal wall during the ultrasonic irrigation.

$Ca(OH)_2$ remnants left in the root canal can result in a thicker non-homogenous appearance of root canal sealers (Margelos et al. 1997, Kim & Kim 2002, Hosoya et al. 2004). The sealer thickness could have an effect on the sealing ability of root canal fillings (Kontakiotis et al. 1997). The $Ca(OH)_2$ remnants could also result in a chemical reaction with the sealer resulting in a reduction of flow or working time (Margelos et al. 1997, Hosoya et al. 2004). Cracks were visible in zinc-oxide eugenol sealer after the use of $Ca(OH)_2$ (Kim & Kim 2002) which can be explained by the faster setting of the sealer under the influence of $Ca(OH)_2$ (Margelos et al. 1997). $Ca(OH)_2$ remnants could also prevent sealer from penetrating the dentinal tubules resulting in a potential reduction in sealer adaption (Çalt & Serper 1999). The dimensional instability of $Ca(OH)_2$ and its potential to dissolve in water and dissociate into hydroxide and calcium ions (Cohen & Burns 2002) could influence the leakage of root fillings on the long term. In the past, leakage studies have been undertaken to evaluate the influence of the above mentioned phenomena on the leakage of a root canal fillingex vivo. However, most of these studies were passive dye leakage studies which are not reliable because $Ca(OH)_2$ discolours methylene blue (Wu et al. 1998), which is often used as a colouring agent for dye leakage. Further more dye leakage is a passive leakage test which can hinder the penetration of dye when air bubbles are present between the root filling and the root canal wall (Wu et al. 1994). Because the studies were performed directly after filling the root canals the effect on the long term could not be evaluated. Therefore, a negative effect of $Ca(OH)_2$ remnants on leakage of subsequently placed root fillings on the short and long term has never been demonstrated.

In a study by Lee et al. (2004a) a standardized groove was cut in the apical part of the root canal to simulate an oval extension of the apical root canal. The dimensions of the groove were determined using the data of the anatomy of the apical root canal as described by Wu et al. (2000). Using this methodology the removal of calcium hydroxide paste packed in an apical extension, which can not be removed by endodontic files, but can only be removed by irrigation, could be evaluated while the situation before irrigation is controlled.

The purpose of the study was to evaluate the capacity to remove $Ca(OH)_2$ from an artificial standardized groove in the apical root canal and to evaluate the efficacy of $Ca(OH)_2$ removal during passive ultrasonic irrigation between NaOCl and water.

Materials and methods

Sixteen mandibular single rooted premolars were selected after bucco-lingual and mesio-distal radiographs indicated that their internal diameters at three points (2, 4 and 6 mm from the apex) were smaller than the corresponding diameters of a size 30, 0.06 taper GT instrument (Dentsply Maillefer, Ballaigues, Switzerland). The crowns of the teeth were removed 12 mm from the apex to standardize the length of the roots and eliminate the variation in dimension of the pulp chamber. The root canals were shaped with GT root canal instruments, to a size 30, 0.06 taper GT instrument as the master apical file. Each canal was prepared to the apical foramen which was determined by inserting a size 10 K-file into the canal until the tip of the file was just visible. Between each instrument, the canals were irrigated with 2 mL of a freshly prepared 2% solution of sodium hypochlorite (NaOCl), using a syringe and a 27-gauge needle that was placed 1 mm short of the working length, resulting in a total volume of 30 mL. The NaOCl solution was prepared by diluting a 10% NaOCl solution (Merck, Darmstadt, Germany). Its pH was adjusted to 10.8 with 1 N HCl. The concentration of the NaOCl solution was measured iodometrically (Moorer & Wesselink 1982).

After root canal preparation each root was split longitudinally through the canal, forming two halves. A standard groove of 4 mm in length, 0.2 mm in width and 0.5 mm in depth was cut in one canal wall 2 to 6 mm from the apex, to simulate uninstrumented canal extensions in the apical half (Lee et al. 2004a)(Figure:1). Each groove was filled with calcium hydroxide paste (Ultracal ® XS, Ultradent Products, Jordan, Utah, USA) using paper points 30- 40, to simulate a situation when calcium hydroxide paste remains in natural canal extensions after instrumentation. Care was taken to consistently apply the calcium hydroxide paste in the groove. The teeth were reassembled with wires and stored for one week at 37˚C in 100% relative humidity to simulate the clinical situation when $Ca(OH)_2$ is used as an intermediate root filling between two treatment visits. After one week of storage, images of each half of the canal with a groove were taken using a Photomakroskop M 400 microscope with a digital camera (Wild, Heerbrugg, Switzerland) at x 40 magnification to detect the amount of $Ca(OH)_2$ just before irrigation; the photos were then scanned as tagged-image file format images. The two root halves were reassembled by means of wires and sticky wax, and the apical foramen was sealed with wax. Three different types of irrigation were tested with the sixteen teeth; a pilot study had demonstrated that the smooth wire used during ultrasonic irrigation did not damage the root dentine or alter the form of the groove. In group 1 (n=16) the root canals were ultrasonically irrigated for 3 minutes with a continuous flow of 50 mL 2.0% NaOCl. Group 2 (n=16) was the same as group 1 with the exception that water was used as the irrigant in place of 2%

NaOCl. In group 3 (n=16) the canals were irrigated with 50 mL of 2.0% NaOCl using a syringe with a 27 gauge Therumo needle (Terumo Europe N.V., Brussels,Belgium) which was inserted just short of the apical foramen. Ultrasonic irrigation was performed with a piezoelectronic unit (PMax: Satelec, Meriganc, France). After switching on the ultrasonic device, an activated 21mm long stainless steel smooth wire with a diameter of 0.15 mm and a 0.02 taper (van der Sluis et al. 2005a) was placed in the canal just short of the apical foramen, the oscillation of the wire and irrigation began almost at the same time. The oscillation of the wire was directed towards the groove and the intensity was set on speed 'blue 4'. According to the manufacturer, the frequency employed under these conditions was approximately 30 kHz, and the displacement-amplitude varied between 20 and 30 µm. Between the different irrigation procedures the root halves containing the groove were cleaned with brushes and air under high pressure. The grooves were examined under a microscope to ensure that all $Ca(OH)_2$ remnants were removed from the grooves. The root halves were separated after each irrigation procedure in order to evaluate the removal of $Ca(OH)_2$. After irrigation, images of each half of the canal with a groove were taken using a Photomakroskop M 400 microscope with a digital camera (Wild, Heerbrugg, Switzerland) at x 40 magnification; the photos were then scanned as tagged-image file format images.

The quantity of $Ca(OH)_2$ in the groove before and after irrigation was scored double blind and independently by three calibrated dentists using the following scores, score: 0 the groove is empty, score:1 less than half of the groove is filled with $Ca(OH)_2$, score: 2 more than half of the groove is filled with $Ca(OH)_2$, score: 3 the groove is filled completely with $Ca(OH)_2$. With the scores before and after irrigation, the percentage of score reduction was calculated as follows:

$$\text{Percentage of score reduction} = \frac{\text{Score before irrigation - Score after irrigation}}{\text{Score before irrigation}} \times 100\%$$

The differences in $Ca(OH)_2$ scores between the different groups were analysed by means of the Kruskal-Wallis and Mann-Whitney tests. The level of significance was set at
$p = 0.05$.

Results

The results of the study are shown in Table 1. The $Ca(OH)_2$ score was reduced by 63.3% in group 1, 6.7% in group 2 and 16.7% in group 3. The difference between all groups was
statistically significant (K-W Test $p<0.001$). Group: 1 differed significantly from group 2 ($p<0.001$) and 3 ($p=0.002$) but there was no significant difference between group 2 and 3 ($p=0.765$).

Discussion

The results indicate that PUI with NaOCl as irrigant was more effective in removal of $Ca(OH)_2$ paste from an artificial standardized groove in the apical root canal than PUI with water or irrigation by means of syringe delivery of NaOCl.

During PUI acoustic microstreaming and cavitation can occur which cause a streaming pattern within the root canal from the apical to the coronal (Ahmad et al. 1987a, Roy et al. 1994). Due to this microstreaming more dentine debris can be removed from the root canal compared to syringe delivery of the irrigant (Lee et al. 2004b), even from remote places in the root canal (Goodman et al. 1985). Probably the same mechanisms are responsible for the more effective removal of $Ca(OH)_2$ during PUI in comparison to syringe delivery of the irrigant.

Sodium hypochlorite as irrigant is more effective in removing dentine debris from the root canal during PUI than water (Huque et al. 1998, van der Sluis et al. in press). Since 30% of dentine debris is organic material, the excellent organic tissue dissolution properties of NaOCl were suggested as an explanation (van der Sluis et al. in press). To examine if the organic tissue dissolution properties are really of importance for the effectiveness of PUI with NaOCl as irrigant, the removal of a non-organic substance from a standardized groove in a root canal during PUI could give an answer. The capacity to remove a non-organic substance from a standardized groove in a root canal during PUI can evaluate the importance of the tissue dissolving effect of NaOCl during PUI. NaOCl as an irrigant during PUI is also more effective in removing $Ca(OH)_2$ from an artificial groove in the apical root canal than water, as it is during the removal of dentine debris. The results of PUI with water were comparable with the results of irrigation by means of syringe delivery of NaOCl indicating that the extra capacity to remove matter from the root canal of PUI with NaOCl as irrigant does not occur when water is used. Because $Ca(OH)_2$ is an in-organic substance the tissue dissolving capacity of NaOCl cannot play a role in the process. There are several explanations for differences between water and NaOCl as irrigant during PUI. First the physical properties of NaOCl are different from water, NaOCl is a salt water suspension, normal water not. Bubbles formed in salt water tend to be more numerous, particularly regarding the smallest bubbles and are less prone to coalesce than bubbles in fresh water (Leighton 1994). Because the smallest bubbles are more numerous, the acoustic microstreaming will be different and could perhaps be more powerful. Another explanation is that gas will dissolve in the bubble during cavitation and the oscillations of the bubble depend on the concentration of the gas dissolved in the liquid, the temperature of the liquid and small amounts of surface active impurities (Brenner et al. 2002). During PUI with NaOCl as irrigant, chlorine gas will be present in the irrigant which can dissolve in the bubble. The chlorine gas in the irrigant will also have an influence on the oscillation of the bubbles. This will influence the acoustic microstreaming. Whether the temperature and surface active impurities during PUI are different with NaOCl or water as an irrigant is not known. All these items remain for further research.

In this study, the most successful method of $Ca(OH)_2$ removal was PUI with NaOCl as irrigant; an average of 63.3% of $Ca(OH)_2$ removal was recorded. In earlier studies higher percentages of dentine debris removal and more samples with a completely empty groove were recorded (Lee et al. 2004b, van der Sluis et al. 2005b, van der Sluis et al. 2006 in press)(Table:2). However, root canals of different sizes and tapers were used varying from apical sizes 50, 30 and 20 and tapers of 0.10 - 0.06. It is more difficult to remove dentine debris from the root canal when the size and taper of the root canal are smaller (Lee et al. 2004a, van der Sluis et al. 2005b). However, the average removal of $Ca(OH)_2$ from a size 30 taper 0.06 was even lower than the scores of dentine debris removal from a smaller root canal of size 20 and taper 0.06. This could indicate that it is more difficult to remove $Ca(OH)_2$ from the root canal wall than dentine debris. The remaining 36.7 % $Ca(OH)_2$ residue could have a negative effect on the sealing abilities of sealers, prevent sealers from penetrating the dentinal tubules or dissolve with time (Margelos et al. 1997, Çalt & Serper 1999, Kim & Kim 2002, Cohen & Burns 2002, Hosoya et al. 2004).

No irrigation with EDTA was used in this study. EDTA may neutralize $Ca(OH)_2$ residues to prevent chemical influence on the sealer, however the interference from the mechanical point of view is still present (Margelos et al. 1997). Çalt & Serper 1999 reported complete removal of $Ca(OH)_2$ from the root canal after irrigation with EDTA and NaOCl in comparison with NaOCl alone. It is likely that EDTA may chelate residual $Ca(OH)_2$ which is then more easily removed by irrigation with NaOCl (Margelos et al. 1997). However, other studies using the same irrigation regime (EDTA and NaOCl) could not confirm these results and still found extensive remnants of $Ca(OH)_2$ (Tatsuta et al. 1999, Lambriandis et al. 2006). There is no evidence that EDTA can completely dissolve $Ca(OH)_2$ placed superficially on the canal wall or from deeper layers of the root canal. However, it could be interesting to study if pretreatment of $Ca(OH)_2$ with EDTA removes $Ca(OH)_2$ more easily from the root canal during PUI than no pretreatment of EDTA.

In this study Ultracal® XS was used as the calcium hydroxide paste. UltraCal ® XS is an aqueous radiopaque paste with a pH of 12.5. The approximate $Ca(OH)_2$ concentration is 35%. If another type of calcium hydroxide paste would have given different results is not known but since this is an aqueous solution of $Ca(OH)_2$ no influence from the vehicle is expected.

Conclusion

Passive ultrasonic irrigation with 2 %NaOCl is more effective in removing $Ca(OH)_2$ from the root canal than syringe delivery of 2% NaOCl or water as irrigant during PUI.

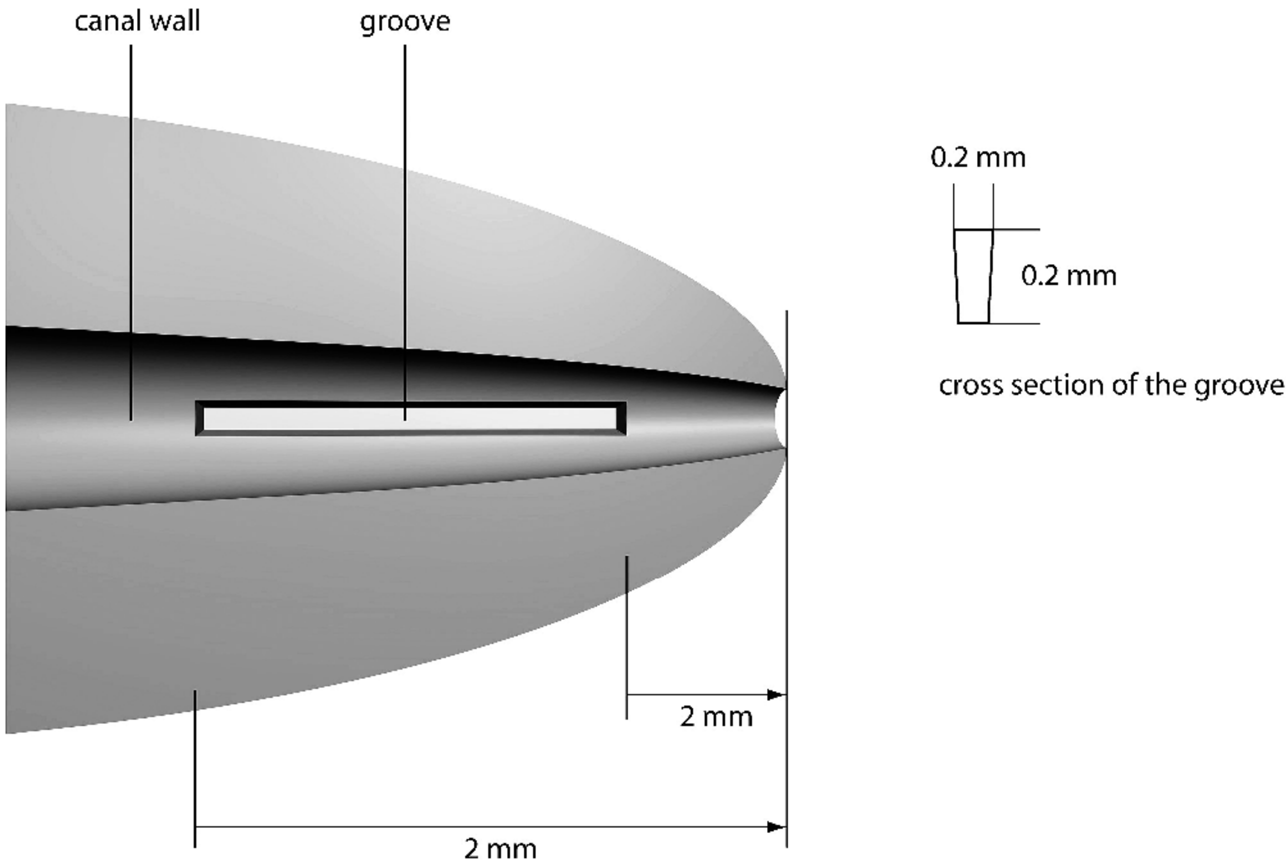
Table 1 Score of $Ca(OH)_2$ before and after irrigation and the percentage of score reduction

groups	before	after		percentage of score reduction	
		mean	SD	mean	SD
1	3.00	1.1	1.1	63.3	36.7
2	3.00	2.8	0.5	6.7	16.7
3	3.00	2.5	1.0	16.7	33

Table 2 Percentage of dentine debris or $Ca(OH)_2$ removal from an artificial groove in the apical root canal in different studies

Study	Size	Taper	Irrigation	Reduction (%)	Score 0 (%)
Lee *et al.* (2004a), dentine debris	50	SB	US NaOCl	88	75
	50	SB	S NaOCl	25	0
van der Sluis *et al.* 2005b, dentine debris	20	0.10	US NaOCl	92.7	87
van der Sluis *et al.* (2006), dentine debris	20	0.10	US NaOCl	98	93
	20	0.10	US water	44	20
$Ca(OH)_2$	30	0.08	US NaOCl	63.3	37.5
	30	0.08	US water	6.7	0
	30	0.08	S NaOCl	16.7	6.25

Figure 1
Schematic representation of the groove model



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A comparison between passive ultrasonic irrigation (PUI) and hand irrigation to remove pulp tissue and dentine debris from the apical portion of the root canal. An in situ investigation

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Abstract

Aim To compare the efficacy to remove pulp tissue and dentine debris from the apical root canal during passive ultrasonic irrigation (PUI) and hand irrigation.
Methodology The mesio-buccal root canals of mandibular molars with periapical radiolucencies were instrumented to size 30, taper 0.06, immediately after extraction, while the mesio-lingual root canals were not treated. Group: 1 received a final irrigation of 45ml 5.25% NaOCl using hand irrigation, group: 2 using PUI. The root canals were fixed with 10% formalin and decalcified. Histological sections were cut horizontally: 3 and 2 mm from the apex, haematoxyline-eosin stained and evaluated using light microscopy. The percentage of organic and inorganic debris was compared. The difference in results was analyzed with the Mann-Whitney *U*-test.
Results The average area of debris was significantly smaller in PUI irrigated root canals ($p<0.001$).
Conclusion PUI removed significantly more pulp tissue and dentine debris from the root canal.

Introduction

Apical periodontitis is an inflammatory process in the periradicular tissues caused by microorganisms in the root canal system (Kakehashi et al. 1965, Möller et al. 1981). The aim of root canal treatment is the prevention or treatment of apical periodontitis (Haapasalo et al. 2005), which includes the elimination of infection from the root canal and the prevention of reinfection (Sjögren et al. 1990). Elimination of infection is difficult and when instrumentation is combined with hand irrigation still microorganisms can be found in the apical root canal after endodontic treatment (Ricucci & Bergenholtz 2003, Naïr et al. 2005).

Passive ultrasonic irrigation (PUI), is ultrasonic activation of an irrigant in the root canal, using an ultrasonically oscillating small file or smooth wire (e.g. size:15, 20)(van der Sluis et al. 2005a) placed in the centre of the root canal, after the root canal has been shaped up to the master apical file (Ahmad et al. 1987). PUI with sodium hypochlorite (NaOCl) as the irrigant, removes more dentine debris, bacteria and vital pulp tissue from the root canal than hand irrigation (Goodman et al. 1985, Metzler & Montgomery 1989, Lee et al. 2004, Gutarts et al. 2005, Passarinho-Neto et al. 2006).

Histology is an accepted and important methodology to study the effect of PUI because it is the only method to study the removal of pulp tissue from the root canal (Goodman et al. 1985, Metzler et al. 1989, Gutarts et al. 2005, Passarinho-Neto et al. 2006). However, normally the teeth, which are used for in vitro studies, have been stored for some time and the storage medium is mostly a 10% formalin solution. This time period between extraction and treatment and storage medium could influence the structure of pulp tissue and therefore the results do not always reflect the in vivo circumstances. Therefore in this study the teeth were instrumented and irrigated immediately after extraction and therefore it was possible to mimic the clinical situation.

The apical oval root canal is a challenge to clean. Almost 60% of the root canal wall of the apical oval root canal will not be touched by instruments when a rotation preparation technique is used (Wu et al. 2003, Hülsmann et al. 2005). These untouched areas of the root canal wall can only be cleaned by irrigation.

The purpose of this study was to compare the efficacy of PUI and hand irrigation in the removal of pulp tissue and dentine debris from the apical part of the root canal using histology.

Materials and Methods

Study design

For this study non endodontically treated mandibular molars with a periapical radiolucency were used immediately after extraction. The presence of granulation tissue at the apex of the root was confirmed after extraction. Because the root canals were instrumented and irrigated within ten minutes after extraction the pulp tissue still obtained its original structure. Only the mesio-buccal (MB) canals were treated, the mesio-lingual (ML) canals were untreated, serving as control. The apex of the mesial root was covered with wax to close the apical foramen and prevent extrusion of irrigation solution.

Instrumentation and irrigation in MB canals

Immediately after extraction access cavities were prepared and the root canals were shaped. The access cavity was rinsed with a daily freshly prepared 5.25% sodium hypochlorite (NaOCl) solution. The NaOCl solution was prepared by diluting a 10% NaOCl solution (Merck, Darmstadt, Germany) and its pH adjusted to 10.8 with 1 N HCl. The concentration of the NaOCl solution was measured iodometrically (Moorer & Wesselink 1982). Before the MB canal was prepared, the ML and distal (D) canal orifices were sealed with Cavit (Espe AG, Seefeld, Germany) in order to protect the actual content of the root canal. The MB canal was prepared to the apical foramen which was determined by inserting a size 15 K-file (Dentsply Maillefer, Ballaigues, Switzerland) into the canal until the tip of the file was just visible. The root canals were prepared with the GT rotary system (Dentsply Maillefer) in a crown-down sequence starting with file size 35, taper 0.12 for the coronal flaring followed by a series of size 20 and 30, 0.10-0.04 taper. The final file (master apical file, MAF) for each root canal was size 30, 0.06 taper. EDTA paste (File Eze, Ultradent, South Jordan, Utah, USA) was placed on each file as lubricant. Between the instruments, each canal was irrigated with 2 mL of a 5.25% solution of NaOCl, using a syringe and a 30 gauge needle that was placed as deep as possible in the root canal but not deeper than 1 mm short of working length (WL). Thereafter the canals were filled with a 17% solution of EDTA (Salvisol, Pierre Rolland, Meriganc Cedex, France), using a syringe and a 30 gauge needle, for 1 minute to remove the inorganic smear layer.

The teeth were randomly assigned to two groups. The root canals were finally irrigated with 45 mL of 5.25% NaOCl for three minutes using a syringe with a 30 gauge needle that was placed 1 mm short of WL in group one (n= 15) and with PUI using a continuous flow of 15 mL min^{-1} in group two (n=16). A smooth stainless steel wire of size 15, taper 0.02 was inserted until 1 mm short of WL and was ultrasonically activated by a piezoelectronic unit (PMax:Satelec, Meriganc Cedex, France) (van der Sluis et al. 2005a). The oscillation of the wire was performed in bucco-lingual direction at power setting ‘ blue’ 2. According to the manufacturer, the frequency used under these conditions was approximately 30 kHz and the displacement amplitude was 28 µm.

Histology

After irrigation the root canal was dried with paper points (Dentsply Maillefer) and the canal orifice was sealed with Cavit. The teeth were decoronated with a diamond bur in the airrotor (KaVo Dental GmbH Biberach Germany) and the mesial roots were reduced to a length of 12 mm. Each canal was filled with a 10% neutral buffered formalin solution using a syringe and a 27 gauge needle to allow the canal content for fixation. A vertical groove was placed in the buccal surface of the mesial root with a round excavation bur # 10 (Hager & Meisinger GmbH, Neuss, Germany) to help maintain root orientation and aid in canal identification. Each root was immediately placed into a 20 mL vial of 10% formalin and labeled. The roots remained in these vials until histological processing was started.

After fixation the teeth were decalcified with an EDTA solution. Of each root two small block sections of 2 and 1 mm were cut with a scalpel respectively 0-2mm and 2-3 mm from the apex. These sections were embedded in paraffin, according to standard procedures. At both the 2 and 3mm level, four 5-µm thick sections were cut and stained with haematoxyline-eosin (HE). The section at each level that showed the largest debris area was selected for evaluation.

Analytic procedure

Pictures of the sections were taken under a Zeiss Axiocam microscope (Carl Zeiss Vision GmbH, Hallbergmoos, Germany) at ×40 magnification. These photographs were then scanned as Tagged Image File Format (TIFF) images. Using a KS 100 Imaging system 3.0 (Carl Zeiss Vision GmbH) the area of the canal and debris were outlined by hand and calculated by the software and the percentage of debris in the root canal was calculated by the software. Because it was not possible to clearly differentiate between dentine debris and pulp tissue, the percentage of debris in the root canal was calculated. Debris was defined as: pulp tissue remnants or dentine chips, following the definition of Biffi&Rodrigues (1989). These procedures were undertaken by the principal investigator (LS) and controlled by two independent investigators. A difference of opinion of 5% was accepted, if the difference was more than 5%, a compromise was established.

The percentage of tissue and debris present in the root canals were statistically analyzed with the Mann Whitney test and p was set at 0.05.

Results

The amount of debris was significantly less in PUI irrigated root canals than in hand irrigated root canals ($p<0.001$) Table: 1. For PUI irrigated canals the amount of debris was 95% less than in untreated ML canals and for hand irrigated canals the amount of debris was 67% less than in untreated ML canals. The percentage of clean root canal area at the 2 mm level was 29% for hand irrigated canals and 80% for PUI irrigated canals and at the 3mm level 43% for hand irrigated canals and 81% for PUI irrigated canals. No significant difference was found between the percentage of tissue area in the untreated ML canals of both groups ($p=0.560$) (Table: 1). The area of the root canal after instrumentation and irrigation was not significantly different between the groups ($p=0.475$) Table: 2.

Discussion

From the results of this study can be concluded that PUI is more effective than hand irrigation in removing pulp tissue and debris from the apical root canal. These results are in line with other studies where PUI is more effective than hand irrigation in removing vital pulp tissue or dentine debris from the root canal (Lee et al. 2004, Gutarts et al. 2005, Goodman et al. 1985, Metzler et al. 1989, Passarinho-Neto et al. 2006). Acoustic streaming and cavitation induce a powerful streaming of the NaOCl in the root canal during PUI and are an explanation for the efficacy of PUI (Ahmad et al. 1987, Roy et al. 1994).

Because ledging of the root canal is a problem associated with PUI (Goodman et al. 1985), in this study a small stainless steel smooth wire (size 15 taper 0.02) in place of a cutting K-file was used. The end of the wire was slightly precurved. Although the irrigation time was three minutes, no visible ledging could be detected in the PUI group and the mean diameter of both groups was comparable excluding excessive over instrumentation in the PUI group.

The efficacy of hand irrigation and PUI is influenced by the width of the root canal (Senia et al. 1971, Albrecht et al. 2004, van der Sluis et al. 2005b). In this study there was no significant difference between the area's of the root canals of the two groups after instrumentation and irrigation indicating this could not have influenced the results of the study (Table: 2 ($p= 0.475$)).

In this study the untreated ML canals served as control for the treated MB canals because the curvatures of these canals in mesio-distal and bucco-lingual direction

(Cimilli et al. 2006) as well as the dimension of the root canal at 2 and 5 mm from the apex (Wu et al. 2000) are comparable.

In this study it was possible to evaluate the removal of tissue from the root canal. Because the teeth were treated immediadely after extraction this methodology could exactly mimic the clinical situation.

Conclusion

PUI removed significantly more pulp tissue and dentine debris from the apical root canal than hand irrigation.

Table 1 Mean % of debris area in treated root canals (2 and 3 mm combined) and untreated root canals (3mm)

irrigation	**mean ± SD in treated canals**	**N**	**mean ± SD in untreated canals**	**N**
hand	23.2 ± 26.4 *	28	70.6 ± 28.7§	15
PUI	3.2 ± 7.5 *	31	64.0 ± 33.2§	14

* $p < 0.001$
§ $p = 0.560$

Table 2 Mean area of the MB root canal at 2 mm level (mm^2) after instrumentation and irrigation

irrigation	**mean ± SD**	**P**
hand	0.16 ± 0.03	0.475
PUI	0.18 ± 0.04	

Figure 1 *Cross section at the 2 mm level, clearly visible are the treated MB canal (PUI) (right under) and the untreated ML canal (left upper) with in between the isthmus (magnification 20X). The untreated canal was filled with pulp tissue*

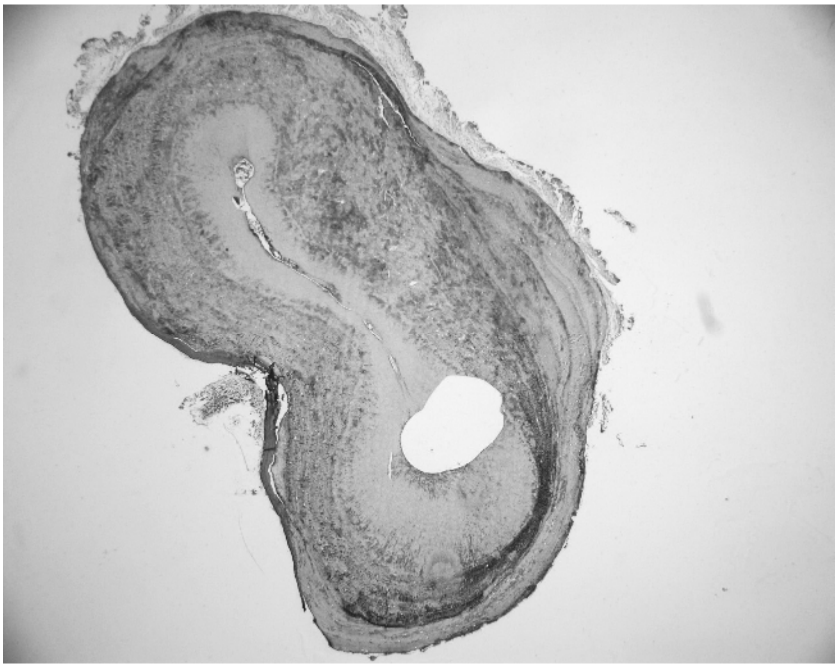


Figure 2 *Cross section at the 3 mm level showing the MB canal filled with pulp tissue and dentine chips (hand irrigation) (magnification 40X)*

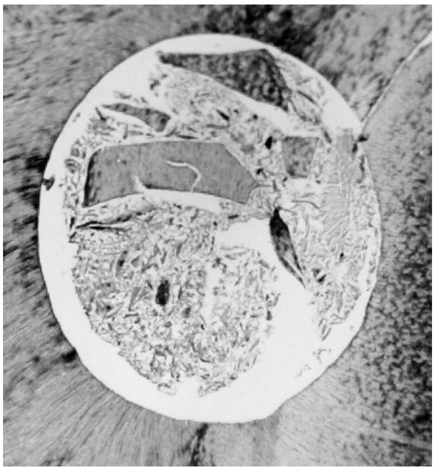
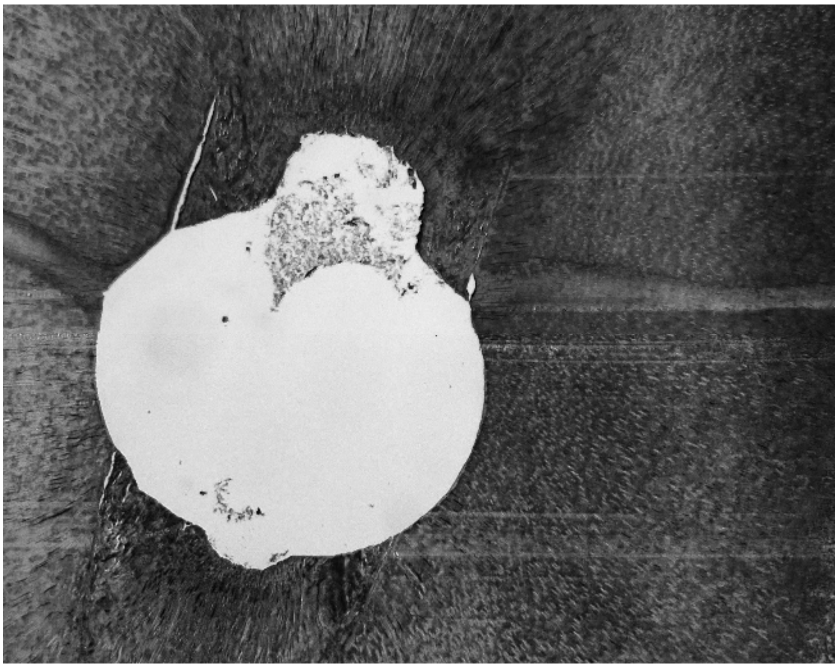


Figure 3 *Cross section at the 3 mm level showing an unclean oval shaped MB canal. The recess of the oval canal was filled with pulp tissue (hand irrigation)(magnification 40X)*



13

Discussion and conclusions

Discussion and conclusions

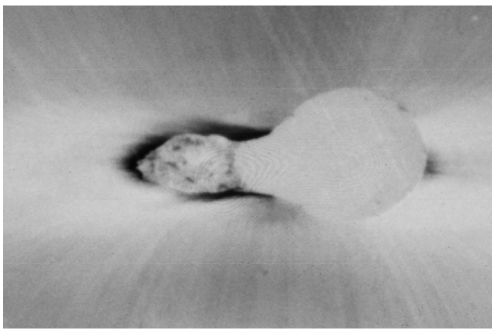
Instrumentation

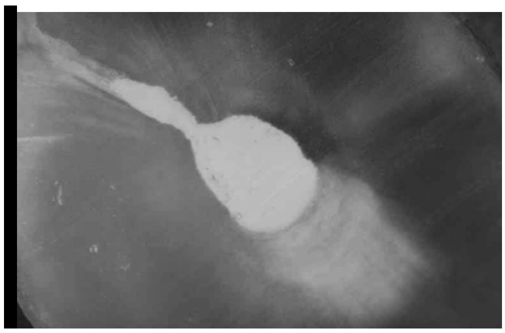
In the apical part of oval canals, both the balanced force technique, that uses a rotary motion of the instrument and circumferential filing leave large portions of the canal wall uninstrumented (61.4% for the balanced force technique and 42.3% for the circumferential filing). Irrigation is therefore indispensable to remove pulp tissue, dentine debris and microorganisms from the root canal (chapter two). This conclusion is supported by the outcome of other research (Peters 2004, Hülsmann et al. 2005). These two instrumentation techniques are representative for the root canal instrumentation techniques presently available. This indicates that an efficient irrigation system in endodontics is necessary. The more powerful the irrigation system, the more the instrumentation can be limited which will decrease the risk of vertical root fracture (Trope&Ray 1992, Zandbiglari et al. 2006) (chapter:three).

Oval canals

Apart from the fact that an oval root canal is difficult to instrument, also filling is attended with some problems, in view of the fact that the quality of root fillings in oval canal mandibular incisors may be compromised (chapter four). This should be considered as a problem, because a substantial number of tooth groups have apically oval shaped root canals (Wu et al. 2000). However, cleaning seems to be a larger problem than filling per se because the defected root fillings were primarily caused by dentine debris left in the root canal after chemo-mechanical cleaning (Wu&Wesselink 2001). Luckily, passive ulrasonic irrigation (PUI) can remove more dentine debris from the root canal than hand irrigation resulting in root fillings with a better *adaptation* to the *root canal wall* and an improved *sealing* of the *root canal* (chapter five). When dentine debris is removed from the irregularities of the root canal wall or from oval extensions of the root canal (fig.: 1), filling material can flow easily in these areas and therefore adapt better to the root canal wall (Ardilla et al. 2003). With the results of the study described in chapter five, we can for the first time see a direct relation between irrigation of the root canal and the sealing quality of a root canal filling.

Figure 1 (left) oval extension filled with dentine debris, root canal is irrigated with handirrigation (right) clean oval extension after PUI, filled with gutta-percha





Passive Ultrasonic Irrigation (PUI)

PUI appeared to be more efficient than hand irrigation in the removal of vital pulp tissue, dentine debris and bacteria from the root canal (conclusion chapter six). Nevertheless, it is important to further intensify research on PUI because the mechanisms behind it are not yet fully understood. The influence of frequency and intensity on the irrigation process is still unknown. Furthermore, the role of cavitation is still unclear. From primary test results visualizing NaOCl activated by ultrasound with a high-speed camera in a glass replica of a root canal, it appeared as if stable and transient cavitation both concurrently occur (fig.:2). Cavitation may enforce acoustic streaming and aid in removing the biofilm from an infected root canal.

As far as instruments used during PUI are concerned, this thesis shows that a smooth wire is as effective as a cutting K-file (chapter seven). More research is needed to find the optimum material and surface properties of the instrument for transmission of the ultrasonic energy to the irrigant.

Figure 2 (left) Glass root canal model allowing optical access to the vibrating file for high-speed visualization of ultrasonic irrigation.(middle) File in operation captured at microseconds timescale displaying both transient and inertial cavitation phenomena and in addition local streaming patterns (only visible in video mode). (right) A high speed recording of a non cutting K file is shown, displaying vigorous microstreaming and collapsing cavitation bubbles.

PUI parameters

Dimension and taper of the root canal have an influence on the efficacy of hand irrigation (Senia et al. 1971, Albrecht et al. 2004) and PUI (conclusion of chapter eight). Within the limits of this research design, a larger apical taper of the root canal resulted in more dentine debris removal from the apical root canal. The size of the root canals had been enlarged until an apical diameter of 0.2 mm and the taper varied from 0.06 to 0.10 mm (a taper 0.06 means that the diameter of the canal increases 0.06 mm every mm more coronally in the root canal). According to instructions of the manufacturer, the displacement amplitude of the wire was 28 µm, hence free oscillation of the wire was possible to all groups. Remains the fact that the smaller the taper of the root canal, the higher the possibility the wire touches the root canal wall during irrigation, which will result in a less energetic streaming velocity of the irrigant (chapter six). Higher frequency of ultrasound could possibly compensate for this reduction of energy. This should be further studied.

Whether *coronal* dimensions of the root canal play a role in this process is unknown and will be discussed later.

The lack of a clear instruction protocol was a problem associated with PUI. Therefore the studies described in chapter nine and ten focused on two irrigation methods used during PUI namely the continuous flush technique or the intermittent flushing technique (Cameron 1988). During the intermittent flush technique, the irrigant is injected *directly* in the apical root canal by a syringe and needle. Thereafter an ultrasonically oscillating instrument (file or smooth wire) activates the irrigant in the root canal during which microorganism, dentine debris or organic tissue can be detached from the root canal wall and will be absorbed or dissolved in the irrigant (Weller et al. 1980, Moorer & Wesselink 1982). This will be followed by refreshment of the irrigant and a new activation. Three sequences of 20 seconds of ultrasonic activation followed by 2 ml of fresh NaOCl show the best results. New, still unpublished data, showed that the *three* sequences are indeed needed for the best result. During the continuous flush technique the irrigant continuously flows in the pulp chamber of the tooth and has to be transported to the apical root canal by the streaming of the irrigant in the root canal generated by the ultrasonic stimulation. How effective this transportation is, is not known and is impossible to control.

The intermittent flush technique appeared to be related with some advantages when compared to the continuous flush technique mainly because the refreshment of NaOCl in the apical root canal is more efficient and can be controlled. This refreshment is important because the active part of NaOCl is very unstable. One advantage is the time reduction of the irrigation for each canal from three minutes to one minute. Acceptance of PUI in general practice could be easier because of this time reduction. The heating of NaOCl is another advantage. Heated NaOCl dissolves more tissue and is more antimicrobial. Furthermore the efficacy of the irrigation will be less dependent on the coronal dimensions of the root canal when the intermittent flush technique is used because the irrigant does not need to flow from the coronal to the apical root canal. Therefore probably a small coronal parallel preparation with an apical diameter of 0.20 mm and a taper 0.10 would be enough. If there is enough space for the needle of the syringe to reach the apical root canal efficient irrigation after ultrasonically activation of the root canal is possible.

PUI and water as irrigant

From the results of chapters nine-eleven the conclusion can be drawn that water is not as effective as NaOCl as an irrigant during PUI. The tissue dissolving potential and heating of NaOCl are often used as an explanation. To verify this explanation we investigated the removal of $Ca(OH)_2$ from the root canal which is not organic and does not dissolve in NaOCl. The results showed that also $Ca(OH)_2$ was more efficiently removed from the root canal when NaOCl was used as irrigant during PUI. The tissue dissolving potential and the heating of NaOCl can not be the explanation for the result, but NaOCl should induce a more active streaming in the root canal than water. It seems that in salt solutions different kind of bubbles (more small bubbles) occur during ultrasonic activation than in water. Furthermore, gas has an influence on the oscillation pattern of bubbles during cavitation, and here chlorine could have an influence. More research is needed to clarify this difference which could give more insight in the working mechanism of PUI.

PUI and the removal of $Ca(OH)_2$

$Ca(OH)_2$, often used as an interappointment root canal filling, is difficult or impossible to remove from the root canal (Margelos et al. 1997, Kim & Kim 2002, Hosoya et al. 2004, Lambriandis et al. 2006). PUI is more effective in removing $Ca(OH)_2$ from the root canal than hand irrigation but $Ca(OH)_2$ could not be removed completely from the root canal (chapter eleven). The question is if the drawbacks of the remnants of $Ca(OH)_2$, which remain in the root canal after its use, are a more serious problem than the benefits ascribed to $Ca(OH)_2$.

PUI in vivo

The last conclusion of this thesis can be drawn from chapter twelve namely that PUI is also more effective than hand irrigation in the removal of pulp tissue from the apical oval root canal.

The results of this study demonstrate that PUI can also be more effective than hand irrigation in vivo.

From ultrasonic irrigation to ultrasonic activation

Normally we use the term ‘ultrasonic irrigation’. When I tried to clarify the differences between the continuous flush technique and the intermittent flush technique it appeared as if ultrasonic activation is the most important aspect of ultrasonic irrigation. Due to the active streaming of the irrigant, the irrigant can become a powerful tool to clean the root canal. This aspect could be more important than the flushing effect. Because handirrigation is effective in the removal of loose debris from the root canal, the combination of handirrigation and ultrasonic activation is interesting.

Coronal flaring of the root canal is important for an effective irrigation of the root canal and for the most gutta-percha filling techniques except the single cone technique. Using the above mentioned ultrasonic and handirrigation protocol, coronal flaring of the root canal is not needed for irrigation anymore and can therefore prevent excessive undermining of root structure and vertical root fracture (chapter: 3).

When the output of the ultrasonic activation can increase with an increased frequency, intensity and more effective instruments the preparation size could be limited.

Benefits intermittent flush technique

- combines the best aspects of hand irrigation and ultrasonic activation of the irrigant, namely hand irrigation for an effective and controlled removal of loose debris from the root canal and ultrasonic activation to loosen debris, biofilm from the root canal wall and from oval extensions, and remote areas of the root canal.
- efficient and controlled apical refreshment, opposed to the continuous flush where fresh irrigant has to *flow* or *diffuse* to the apical root canal, while the flow of irrigant during ultrasonic stimulation is directed to the coronal root canal, and no control of apical refreshment is possible.
- refreshment is independent on the coronal dimension of the root canal and therefore the coronal dimension of the root canal can probably be limited.
- heating of NaOCl (always within acceptable limits) in place of cooling (continuous flush) which will result in a better tissue dissolving and antimicrobial capacity of NaOCl.
- time reduction of PUI from three minutes to one minute for each canal is possible due to more efficient apical refreshment.
- no corrosion of the tubings transporting NaOCl through the ultrasonic device.

Benefits PUI in general practice

- better removal of pulp tissue, dentine debris and planktonic bacteria from the root canal than hand irrigation.
- increased tissue dissolving (chemical) and dispersion (mechanical) of NaOCl (increased contact area between NaOCl and pulp tissue).
- improved sealing of root canal filling.
- could lead to a higher healing rate of endodontic treatment due to more efficient removal of dentine debris and pulp tissue and bacteria from the root canal and better sealing of the root canal filling, however this has never been evaluated.
- cheap, simple and fast procedure.

Irrigation protocol

Protocol for PUI:

- use NaOCl as irrigant.
- if the continuous flush technique is used, 3 minutes irrigation per canal is advised, the flush of irrigant can be reduced to 15 mL min^{-1}.
- if the intermittent flush technique is used, 1 minute with three ultrasonic activation sequences of 20 seconds and three times refreshing with 2 mL NaOCl is advised.
- the instrument can be inserted 1 mm short of working length (WL) if it can move freely in the apical part, there seems to be no difference in efficacy of PUI when the instrument is inserted 1-3 mm coronal from WL.
- in a curved canal shaping of the instrument is advised.

Other related aspects of ultrasonic irrigation

This research focused only on PUI (ultrasonic irrigation in the last phase of the root canal treatment). Because no clear definition of ultrasonic irrigation existed, different research methodologies were used resulting in different outcomes. It is therefore not surprising that different opinions and conclusions still exist as expressed in statements like: ‘ it appears from these investigations on the utilization of ultrasonics during and after root canal preparations that ultrasound would have little direct effect on intracanal bacteria (Haapasalo et al. 2005)’, or ‘ the effects of ultrasonic agitation of irrigants have been evaluated with contradictory results (Gulabivala et al. 2005)’. Both authors based their statements on studies where both ultrasonic instrumentation and irrigation were used, two completely different methodologies and therefore with different outcomes. Because the definition was not clearly defined (‘ultrasonics’ or ‘ultrasonic agitation’) and not correctly focused on the issue, the statements are inconclusive (chapter six). This may be another reason why we still can not observe a widespread adoption of the ultrasonic irrigation technique although it is simple, effective and cheap.

The above mentioned facts were for me the motivation for me to use a ‘step by step’ approach and first focus on PUI to systematically clarify this particular detail of ultrasonic irrigation. Of course PUI can be used in the first phase of the root canal treatment if the file or wire can oscillate freely. Although not yet studied, it can be assumed that it will have a positive effect. The cleaner the coronal part of the root canal, the less pulp tissue, microorganisms or dentine debris will be pushed in the periapical region.

Another reason for the limited acceptance of PUI is the lack of good and safe instruments resulting in irregular canal shape, ledging and apical perforation. This drawback may be partially solved as in this study together with Acteon and FKG a new irrigation wire was developed, which is effective and safe to use in the root canal because it has a blunt tip and is non-cutting. Because of its design it can be safely used in the apical root canal without the risk of creating damage or an apical perforation. It is made of stainless steel to make an efficient transmission of the ultrasonic energy to the irrigant possible and to pre-shape it in curved canals.

Future research

An STW funded research program of ACTA-CEP (drs. L. van der Sluis, Prof. P. Wesselink) and Physics of Fluid (POF) of the University of Twente (dr. M. Versluis, Prof. D Lohse) will start from September 2007. The goals of the project are formulated as follows:

- to understand the physical mechanisms of ultrasonic irrigation of root canals as employed today through experiments and numerical simulations. A theoretical model to describe the influence of the frequency and intensity on the irrigation process will be developed.
- to improve the ultrasonic irrigation, by designing new devices and instruments which will make it possible to develop a renewed ultrasonic irrigation technique which will *completely* clean the root canal system from bacteria (planktonic and biofilm), organic and inorganic tissue and dentine debris. The frequency and intensity dependence on the irrigation process will be evaluated. Special attention will be given to canal isthmuses, anastomoses between canals and the apical delta, because all these parts of the root canal are impossible to

clean with the conventional treatment methods . More powerful irrigation solutions (NaOCl with bubbles or coated microbubbles acting as cavitation precursors) will be tested. Also the influence of the instrument design and material on the microstreaming and cavitation will be studied

- to develop an ultrasonic minimal invasive crown-down technique for root canal treatment to save as much root structure as possible.

Conclusions

PUI is a more effective irrigation system than hand irrigation in vitro and in vivo.

Different irrigation systems during PUI (continuous flush, intermittent flush) have different working mechanisms with remarkable advantages for the intermittent flush.

Water is not as effective as NaOCl as irrigant during PUI. PUI with NaOCl result in a more energetic streaming of the irrigant.

Better irrigation leads to better sealing of the root canal filling

PUI removes $Ca(OH)_2$ better from the root canal than hand irrigation.

PUI is a simple and cheap method to improve endodontic treatment in general practice.

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Summary

The first chapter contains a general introduction and the outline of the thesis. In the general introduction, the influence of instrumentation and hand irrigation on endodontic treatment is explained.

In the second chapter the capability of two instrumentation techniques, namely balanced force and circumferential filing, to remove the inner layer of dentine in the apical oval canal is evaluated. During the circumferential filing technique the root canal wall is cleaned with a small file scraping the wall. The balanced-force technique is a rotation technique during which the file instruments the root canal while making rotating movements. This research shows that the balanced force technique removed the inner layer of dentine from 38.6% of the circumference of the canal wall, as opposed to 57.7% using circumferential filing. The difference was not statistically significant (p = 0.101). The conclusion is that in oval canals, both the balanced force and circumferential filing techniques left large portions of the canal wall uninstrumented. Irrigation is indispensable to clean these uninstumented portions of the root canal.

During instrumentation of the root canal, the root canal will be enlarged and therefore dentine will be removed from the root. In the third chapter the force required to vertically fracture uninstrumented and instrumented mandibular premolars (oval canals) and canines (round canals) is compared. No significant difference in resistance to vertical root fracture was found between the round- and oval-canal premolars with (p=0.9) or without (p=0.6) instrumentation. However, the force required to fracture the instrumented premolars and canines was 30% (p<0.05) and 2% (p=0.9) lower, respectively, than that required to fracture their uninstrumented counterparts. This indicates that a root with an oval canal is significantly more weakened by instrumentation than a root with a round canal. Apart from the fact that instrumentation does not completely clean the root canal wall of oval root canals, it also reduces the resistance of roots with oval canals against vertical forces. A more effective irrigation system could limit instrumentation and therefore reduce weakening of the roots and vertical root fracture of the roots. The conclusion of this research is that instrumented mandibular premolars (oval canals) have a higher risk to fracture than the uninstrumented mandibular premolars.

In the fourth chapter the quality of root canal fillings in oval and round canals is evaluated. A group of round and oval canals is filled with gutta-percha and AH-26 as the sealer following the cold lateral compaction technique. The quality of the root fillings is evaluated using different methodologies, namely radiographs to compare the compaction of the root fillings, the fluid transport test (FT) to measure the leakage of the fillings and the percentage of gutta-percha (PGP) to measure the amount of gutta-percha present in the root canal. Also the possible occurrence of a correlation between the different methodologies used was evaluated. The quality of root fillings in oval canals was significantly worse than the quality of root fillings in round canals for all the evaluation techniques with the exception of the compaction of root fillings evaluated with radiograps taken from the bucco-lingual direction. In dental practice radiographs are taken from this direction indicating the difficulty to evaluate the quality of root fillings in dental practice. The correlation between the radiographic score of the mesio-distal radiograph and the PGP was significant. There was no significant correlation between the FT and the radiograph or the FT and the PGP. Probably no correlation between the FT and the other evaluation techniques could be found because this technique only detects voids which run from the coronal to the apical part of the root canal, also when the voids are too small to detect with the other evaluation techniques. It can be concluded that the quality of root fillings in oval canal-mandibular incisors may be compromised.

In the fifth chapter the influence of ultrasonic irrigation on the seal of root fillings in oval root canals is evaluated. Two groups of teeth with oval root canals were filled with gutta-percha and AH-26 as the sealer using a warm vertical compaction technique. In one group the teeth were irrigated with passive ultrasonic irrigation (explanation follows in the next paragraph) before filling, in the other group with hand irrigation. The irrigation time and the amount of irrigant were equal in both groups. As leakage test the recently developed glucose leakage test was used. The advantage of this test is the possibility to expose teeth for a longer period to a fluid under pressure, which makes this test more sensitive than the FT test. The leakage marker is glucose, a small molecule with a dimension comparable to bacteria. Glucose is present in the mouth and serves as nutrition for microorganism, which makes it a clinical relevant marker. Root fillings placed after the teeth were irrigated with passive ultrasonic irrigation leaked significantly less than the root fillings placed after hand irrigation ($p= 0.017$). This research indicates that irrigation of the root canal has a direct effect on the quality of the seal of root fillings and that passive ultrasonic irrigation improves the seal of the root fillings. Therefore passive ultrasonic irrigation reduces leakage of microorganisms or nutrition for microorganisms in the root canal which could have an influence on the occurrence or sustaining of apical periodontitis. The conclusion of this research is that when passive ultrasonic irrigation is used to irrigate the root canal before the filling procedure, the seal of the root canal can be improved.

In chapter six a literature search on passive ultrasonic irrigation (PUI) is described. Ultrasonic irrigation (< 20 Khz) of the root canal is performed with or without simultaneous ultrasonic instrumentation, the latter procedure being termed passive ultrasonic irrigation (PUI). Here the relevant literature on PUI is reviewed from a Medline database search. PUI is performed with a small file or smooth wire (diameter 0.15- 0.20 mm) which oscillates freely in the root canal and induces powerful acoustic microstreaming. PUI can be an important supplement for cleaning the root canal system and compared to traditional hand irrigation PUI removes more organic tissue, planktonic bacteria and dentine debris from the root canal. Also PUI is more efficient than ultrasonic irrigation with simultaneous ultrasonic instrumentation. PUI can also be effective in curved canals and ultrasonic irrigation is more effective than sonic irrigation (1-6 Khz) in the removal of dentine debris from the root canal. The role of cavitation during PUI remains inconclusive. In addition, no detailed information is available on the influence of the irrigation time, the volume of the irrigant, the penetration depth of the instrument and the shape and material properties of the instrument. The influence of the irrigation frequency and intensity on the streaming pattern as well as the complicated interaction of acoustic streaming with the adherent biofilm needs to be clarified to reveal the underlying physical mechanisms of PUI.

Because the development of new instruments for PUI is recent, normally a cutting K-file is used. When this instrument touches the root canal wall during PUI it can lead to undesirable preparation of the root canal wall or even apical perforation, damage of the root tip. A smooth or non-cutting wire could prevent this problem. In the research described in the seventh chapter the efficacy of a smooth wire is compared with a conventional K-file, in removing dentine debris from grooves in root canals made in resin blocks, during ultrasonic irrigation. The dimensions of both instruments were similar. There was no significant difference between the two groups ($p= 0.429$), indicating that the smooth wire is as effective as the cutting K-file. The conclusion was that a smooth wire during passive ultrasonic irrigation is as effective as a cutting K-file in removal of artificially placed dentine debris in grooves in simulated root canals in resin blocks.

The efficacy of PUI could be influenced by the diameter and the form (taper) of the root canal which is investigated in chapter eight. The root canals were instrumented until an apical diamter of 0.20 mm and a taper of 0.06, 0.08 or 0.10 mm. From the root canal with taper 0.06 mm, 74% of the dentine debris was removed. For the groups with taper 0.08 and 0.10 mm this percentage was 81% and 93% respectively. A tendency was found that more dentine debris was removed from root canals with a greater taper but the difference was not statistically significant (p=0.078). It was concluded that a tendency was found that passive ultrasonic irrigation was more effective in removing artificially placed dentine debris from simulated canal extensions from canals with greater tapers.

Little information is available on the influence of irrigation methods, irrigation time, irrigation solution and the volume of irrigant during PUI. In chapter nine and ten, two studies are discussed which try to clarify their influence.

Two irrigation methods are used during PUI namely the continuous flush method and the intermittent flush method. During the first method a continuous flush of irrigant will flow in the pulp chamber. During the intermittent flush method the irrigant solution will be injected in the root canal with help of a syringe and a needle. The irrigant will be activated by an ultrasonically oscillating file or wire. After activation of the irrigant the irrigant will be refreshed by flushing the root canal with 2 ml of fresh irrigant. Hereafter a new ultrasonic activation can follow.

Chlorine, substance of sodium hypochlorite (NaOCl), is responsible for the tissue dissolving potential and the antimicrobial action of NaOCl. Chlorine is unstable and is immediately deactivated after a reaction with organic tissue or microorganisms. Therefore refreshment is important for its efficacy. An advantage of the intermittent flush method is the controlled refreshment of irrigant because the placement of the needle in the root canal and the volume flushed through the apical root canal are known and can be controlled. Using the continuous flush method, control of the apical refreshment is not possible because the irrigant has to flow from the pulp chamber to the apical root canal by the streaming of the irrigant in the root canal induced by ultrasound. If or how this occurs is not known. This research shows that when the irrigation time is set at three minutes, PUI is equally effective in removing dentine debris from the root canal when both irrigation methods are used (p=0.550). No significant difference was seen when during the intermittent flush method every one or every half minute the root canal was flushed with 2 ml NaOCl.

The optimal irrigation time of PUI is unknown. During research often three minutes of PUI for each root canal is used as a standard, which is long in daily practice. From the data of the study described in chapter ten it can be concluded that significantly less dentine debris can be removed from the root canal when the irrigation time was reduced from 3 to 1.5 minutes using the continuous flush method (p=0.017). Using the intermittent flush method a reduction from 3 to 1 minutes did not influence the efficacy of PUI (p=0.550). Probably effective apical refreshment of irrigant takes three minutes when the continuous flush method is used. During the intermittent flush method apical refreshment is more effective and therefore the time can be reduced. Heating of the irrigant will occur during the intermittent flush method which enhances the tissue dissolving potential of NaOCl. During the continuous flush method the irrigant will be cooled. The difference between the cooled irrigant (continuous flush method) and the heated irrigant (intermittent flush technique) is 16 °C.

Dentine debris is better removed from the root canal with NaOCl than with water as irrigant during PUI ($p=0.001$) (chapter: 9 and 10). NaOCl has a strong tissue dissolving potential, antimicrobial action and acts as a lubricant. Because 30% of dentine debris is organic, NaOCl can dissolve this percentage of dentine debris which could be an explanation for its efficacy. Also the heating of NaOCl during PUI will increase its tissue dissolving potential.

The conclusions, which can be drawn from these studies, are that the continuous flush method and the intermittent flush method are two different irrigation methods based on different mechanisms. During the continuous flush method the irrigant has to be transported to the apical root canal by the acoustic streaming of the irrigant. This will probably take three minutes. During the intermittent flush method, apical refreshment is controlled and therefore effective and can be reduced to 1 minute.

Calcium hydroxide ($Ca(OH)_2$) in a non setting paste and is widely used as an intracanal medicament during root canal treatment because of its antimicrobial properties. However, it has been reported that removal of $Ca(OH)_2$ from the apical root canal wall is difficult. Complete removal is important because remnants of $Ca(OH)_2$ could have an influence on the sealing properties of the root canal filling. PUI could be more effective in the removal of $Ca(OH)_2$ than hand irrigation. A comparison in the removal of $Ca(OH)_2$ from the root canal between water and NaOCl as irrigant during PUI could give more information on the difference in efficacy of the two irrigants because $Ca(OH)_2$ is inorganic and does not dissolve in NaOCl. From the results of the research discussed in chapter eleven, it seems that water is not as effective as NaOCl during PUI ($p<0.001$) and that PUI is more effective than hand irrigation ($p=0.002$). There was no significant difference between handirrigation or PUI with water as irrigant ($p=0.765$). When compared with the results of the removal of dentine debris from the root canal, it is more difficult to remove $Ca(OH)_2$ from the root canal than denine debris. The average percentage of removed $Ca(OH)_2$ from the root canal was 63.3% while this percentage can be more than 90% for dentine debris. Because PUI with NaOCl as irrigant is also more effective than PUI with water as irrigant in the removal of $Ca(OH)_2$ from the root canal, the tissue dissolving potential or the heating of NaOCl can not be the reason for this difference. It seems that in salt solutions different kind of bubbles (more small bubbles) occur during ultrasonic activation than in water. Furthermore, gas has an influence on the oscillation pattern of bubbles during cavitation, and here chlorine could have an influence. It can be concluded that NaOCl during PUI has a more effective streaming pattern than PUI with water. Which factors play a role in this process and how remains for further research.

The study discussed in chapter twelve was designed to evaluate if PUI is also more effective than hand irrigation in the removal of pulp tissue from the root canal. The mesiobuccal root canals of lower molars were chemo-mechanically cleaned immediately after extraction. One group was irrigated with PUI as final irrigation, the other group with hand irrigation. Irrigation time and irrigant volumes were similar. The mesiolingual canals served as controls. Because both instrumentation and irrigation were undertaken directly after extraction, the pulp tissue had the same structure as an in vivo situation and a clinical situation could be mimicked. After treatment the root canals were filled with a 10% formalin solution to fix the canal content. Horizontal sections were cut at 3 and 2 mm from the apex of the root and stained with a hematoxiline-eosine staining. Thereafter the area of debris in the root canal sections was measured and calculated. In the group irrigated with PUI, 3.2% of debris was present in the root canal after irrigation. For the hand irrigation group this percentage was 23.2%. This difference was statistically significant ($p<0.001$).

The conclusion is that PUI could remove more pulp tissue and dentine debris from the root canal than hand irrigation. Therefore it is probable that PUI will be more effective than handirrigation in vivo.

Samenvatting

In het eerste hoofdstuk wordt een algemene introductie gegeven tot het proefschrift en de opbouw besproken van het proefschrift. In de algemene introductie wordt een overzicht gegeven van de invloed en effecten van instrumentatie en irrigatie van het wortelkanaal tijdens een wortelkanaalbehandeling.

In het tweede hoofdstuk worden twee wortelkanaal-instrumentatiemethoden (circumferential- filingtechniek en balanced-forcetechniek) geëvalueerd op de mogelijkheid de wanden van een ovaal kanaal te instrumenteren. Tijdens de circumferential-filingtechniek wordt het wortelkanaal gereinigd door met een vijl een schrapende beweging langs de wand van het wortelkanaal te maken. De balanced-forcetechniek is een rotatietechniek waarbij de vijl met een roterende beweging het kanaal instrumenteert. Uit dit onderzoek blijkt dat na met de rotatietechniek het wortelkanaal geinstrumenteerd te hebben, 61.4% van de kanaalwand *niet* wordt geraakt door het instrument en dus *niet* wordt geïnstrumenteerd. Tijdens de circumferential-filingtechniek is dit percentage 42.3%. Er is geen significant verschil tussen de beide groepen. De effectiviteit van de rotatietechniek kan vergeleken worden met de effectiviteit van de op dit moment veel gebruikte mechanische rotatietechnieken. De conclusie van dit onderzoek is dat het niet mogelijk is om met behulp van instrumentatietechnieken de wand van het apicale deel van ovale wortelkanalen geheel te reinigen. Irrigatie van het wortelkanaal is onmisbaar om deze gebieden te reinigen.

Tijdens het instrumenteren van het wortelkanaal wordt dentine verwijderd. In het derde hoofdstuk wordt geëvalueerd in hoeverre een instrumentatietechniek de wortelstructuur van een gebitselement ondermijnt en of er hierin een verschil is voor wortels met een rond of ovaal wortelkanaal. Er werd geen significant verschil gevonden in de kracht die nodig was om een wortel met een ovaal of rond kanaal te breken zowel voor ($p=0.9$) als na instrumentatie ($p= 0.6$). Echter de kracht die nodig was om een wortel met een ovaal kanaal te breken na instrumentatie was 30% lager ($p<0.05$), voor een wortel met een rond kanaal was dit 2% lager ($p=0.9$). Dit houdt in dat een wortel met een ovaal kanaal significant meer wordt verzwakt door instrumentatie dan een wortel met een rond kanaal. Klinische gegevens bevestigen dit resultaat. Buiten dat het instrumenteren van de wortelkanalen de wanden van ovale kanalen niet geheel reinigt, vermindert het ook de resistentie van wortels met ovale wortelkanalen tegen verticale krachten. Een meer effectieve irrigatie van het wortelkanaal zou instrumentatie kunnen beperken en daarmee ook verzwakking van de wortel kunnen voorkomen.

In het vierde hoofdstuk is het verschil tussen ovale en ronde wortelkanalen nader onderzocht met betrekking tot de kwaliteit van de wortelkanaalvulling. Een groep ronde en ovale kanalen zijn gevuld met gutta-percha en AH 26 met behulp van de koude, laterale compactietechniek. De wortelkanaalvullingen zijn geëvalueerd met behulp van drie verschillende evaluatietechnieken welke ook weer onderling zijn vergeleken. De vloeistoffiltratietechniek meet de vochtdoorlaatbaarheid van de wortelkanaalvulling. Voor het bepalen van de compactiegraad van wortelkanaalvulling zijn röntgenopnamen uit twee richtingen gebruikt worden. De hoeveelheid in het wortelkanaal aanwezig vulmateriaal is gemeten in dwarsdoorsneden die op verschillende plaatsen in het wortelkanaal zijn gemaakt. De kwaliteit van de vullingen in ovale kanalen scoort significant slechter bij alle evaluatietechnieken met uitzondering van de bepaling van de compactiegraad met behulp van röntgenfoto's genomen uit bucco-linguale richting. De röntgenfoto's in de praktijk worden vanuit deze richting gemaakt, wat een adequate controle van de vulkwaliteit van het wortelkanaal moeilijk maakt. Er was een significante correlatie tussen enerzijds de techniek die gebruikt maakt van mesio-distale röntgenfoto's en anderzijds de techniek die de dwarsdoorsnede door het wortelkanaal evalueert. Een verklaring voor het ontbreken van een correlatie tussen de vloeistoffiltratietechniek en de andere technieken is dat deze techniek alleen openingen in de vulling kan detecteren die van coronaal tot apicaal lopen. De vloeistoffiltratietechniek kan deze openingen echter ook aantonen wanneer ze zo klein zijn dat deze door middel van de andere evaluatiemethoden niet meer aangetoond kunnen worden. Geconcludeerd kan worden dat wortelkanaalvullingen in ovale kanalen slechter van kwaliteit zijn dan wortelkanaalvullingen in ronde kanalen.

Het vijfde hoofdstuk beschrijft een onderzoek dat de invloed van ultrasone irrigatie op de afsluiting van wortelkanaalvullingen in ovale wortelkanalen onderzocht. Twee groepen elementen met ovale wortelkanalen zijn gevuld met gutta-percha en AH 26 met behulp van een warme, verticale compactietechniek. In één groep werd passieve ultrasone irrigatie toegepast (uitleg volgt in de volgende paragraaf) en in de andere groep handirrigatie. De irrigatietijd en de hoeveelheid irrigatievloeistof waren in beide groepen gelijk. Voor de lekkagetest werd de (recent ontwikkelde) glucoselekkagetest gebruikt. Het voordeel van deze test is dat het mogelijk is om de elementen langere tijd aan een vloeistof onder druk bloot te stellen. Bij de vloeistoffiltratietest wordt meestal een periode van drie uur getest, bij de glucoselekkagetest is het echter mogelijk om de wortelkanaalvullingen een maand of langer aan de lekkage van vloeistof bloot te stellen. Daarom is de glucosetest gevoeliger dan de vloeistoffiltratietest. De lekkagemarker is glucose, een klein molecuul waarvan de afmeting vergelijkbaar is met die van een bacterie. Glucose komt voor in de mondholte en dient als voedingsstof voor bacteriën en is hierdoor een klinisch relevante marker. De wortelkanaalvullingen die zijn aangebracht nadat er passieve ultrasone irrigatie is toegepast lekten significant minder dan de elementen waar geen passieve ultrasone irrigatie was toegepast ($p= 0.017$). Dit onderzoek geeft aan dat irrigatie direct een effect heeft op de kwaliteit van de afsluiting van wortelkanaalvullingen en dat na passieve ultrasone irrigatie de afsluiting beter is. Dit zou de lekkage van bacteriën, of voeding voor bacteriën die in het wortelkanaal aanwezig zijn kunnen verminderen wat een invloed kan hebben op het onstaan of onderhouden van parodontitis apicalis. De conclusie van dit onderzoek is dat het toepassen van passieve ultrasone irrigatie voorafgaand aan het vullen van het wortelkanaal een verbetering geeft van de afsluiting van het wortelkanaal.

Het zesde hoofdstuk is een overzicht van de literatuur over passieve ultrasone irrigatie (PUI).Ultrasone irrigatie (< 20 Khz) van het wortelkanaal wordt uitgevoerd met of zonder gelijktijdige instrumentatie van het wortelkanaal, de laatste procedure wordt passieve ultrasone irrigatie genoemd en is effectiever dan de eerstgenoemde procedure. PUI wordt uitgevoerd met een dunne vijl of gladde naald (diameter 0.15-0.20 mm) die vrij kan oscilleren in het wortelkanaal en een energieke akoestische stroming van de irrigatievloeistof opwekt. PUI is een belangrijke toevoeging aan de endodontische behandeling en vergeleken met handirrigatie verwijdert PUI meer pulpaweefsel, planktonische bacteriën en dentinedebris uit het wortelkanaal. PUI is ook effectief in kromme kanalen en meer effectief dan sonische irrigatie (1-6 Khz). De rol van cavitatie blijft nog steeds onduidelijk omdat er in de literatuur wisselend over wordt gerapporteerd. Geen informatie is bekend over de invloed van de irrigatietijd, het volume van de irrigatieoplossing, de lengte waarop het instrument in het wortelkanaal wordt gebracht, en de vorm en materiaal van het instrument op de effectiviteit va PUI. De invloed van de irrigatiefrequentie en intensiteit op het stromingspatroon van de irrigatievloeistof, het effect van de akoestische stroming op de biofilm en de fysische mechanismen die de effectiviteit van PUI verklaren moeten nog onderzocht worden.

Wanneer PUI wordt uitgevoerd met een snijdende stalen K-vijl dan prepareert de vijl de wand van het wortelkanaal wanneer deze de wand aanraakt. Dit is moeilijk te voorkomen met name in het apicale deel van het wortelkanaal wat kan leiden tot ongewenste preparatievormen of zelfs apicale perforatie, een beschadiging van de wortelpunt. Om dit probleem te vermijden kan een gladde vijl of niet snijdende draad gebruikt worden. In het zevende hoofdstuk wordt een onderzoek beschreven waarin is geëvalueerd of een stalen gladde draad net zo effectief is in het verwijderen van dentinedebris uit een ovale uitloper van het wortelkanaal tijdens PUI als een stalen snijdende K-vijl. De afmeting van beide instrumenten was gelijk. Er bleek geen significant verschil te zijn tussen beide groepen ($p=0.429$), wat erop duidt dat er geen verschil geconstateerd kan worden in de effectiviteit van het instrument tijdens PUI wanneer de dimensies en het materiaal van de vijl of de gladde draad gelijk zijn. De conclusie is dat onder de condities van dit onderzoek een gladde stalen draad net zo effectief is in het verwijderen van dentinedebris uit het apicale deel van een ovaal wortelkanaal als een stalen snijdende K vijl.

De effectiviteit van PUI zou beïnvloed kunnen worden door de diameter en de vorm (taper) van het wortelkanaal. In het achtste hoofdstuk wordt beschreven of dit verschil in effectiviteit aangetoond kan worden wanneer de kanalen zijn geprepareerd tot een apicale diameter van 0.20 mm en een taper van 0.06, 0.08 of 0.10 mm. Uit het kanaal met taper 0.06 mm werd 74% dentinedebris verwijderd. Voor taper 0.08 en 0.10 mm was dit 81% en 93%. Er is een tendens gevonden dat meer dentinedebris wordt verwijderd uit de kanalen met een grotere taper maar dit verschil was niet significant ($p=0.078$). Geconcludeerd kan worden dat er een tendens is dat de vorm van het wortelkanaal een invloed kan hebben op de effectiviteit van PUI en dat bij de hier gebruikte diameter en tapers een grotere taper een meer effectieve PUI toeliet.

Weinig is bekend over de invloed van irrigatiemethoden, irrigatietijd, irrigatievloeistof en volume van de irrigatievloeistof op de effectiviteit van PUI. In het negende en tiende hoofdstuk worden twee onderzoeken besproken die hier meer duidelijkheid over verschaffen.

Er zijn twee irrigatiemethoden mogelijk tijdens PUI namelijk de continue flushmethode en de intermitterende flushmethode. Bij de eerste methode zal een continue stroom van irrigatievloeistof de pulpakamer vullen. De akoestische stroming van de irrigatievloeistof die wordt opgewekt door de ultrasone activatie moet de irrigatievloeistof naar het apicale deel van het wortelkanaal doen stromen. Bij de intermitterende flushmethode wordt de irrigatievloeistof in het wortelkanaal aangebracht met een injectiespuit. De irrigatievloeistof wordt geactiveerd door middel van een vijl of naald die op een ultrasone frequentie oscilleert. Daarna wordt de irrigatievloeistof ververst door het wortelkanaal te spoelen met 2 ml irrigatievloeistof met behulp van een injectiespuit. Hierna kan er eventueel een nieuwe ultrasone activatie van de verse irrigatievloeistof plaatsvinden.

Chloorgas, bestanddeel van natriumhypochloriet (NaOCl), is verantwoordelijk voor het weefsel oplossend vermogen en de anti-bacteriële werking van NaOCl. Chloorgas is echter zeer vluchtig en wordt meteen geïnactiveerd na een reactie met organisch weefsel of micro-organismen. Daarom is verversing erg belangrijk voor de effectiviteit van NaOCl. Een voordeel van de intermitterende flushmethode is dat de verversing controleerbaar is omdat de plaatsing van de naald van de injectiespuit in het kanaal en het volume van NaOCl waarmee gespoeld wordt bekend zijn. Het nadeel van de continue stroommethode is dat beide factoren niet controleerbaar zijn. Er is in de literatuur beschreven dat er tijdens PUI een stroom optreedt van apicaal naar coronaal maar hoe sterk deze stroming is, is niet bekend. Dit blijft dus onzekere factor. De uitkomsten van dit onderzoek geven aan dat bij 3 minuten PUI beide methoden even effectief zijn in het verwijderen van dentinedebris uit het wortelkanaal ($p=0.550$). Bij de intermitterende flushmethode werd er om de halve of hele minuut ververst met 2 ml NaOCl, ook dit gaf geen significant verschil in de effectiviteit van de PUI.

De optimale irrigatietijd van de PUI is onbekend. Er wordt vaak 3 minuten geïrrigeerd omdat dit veelvuldig in de literatuur wordt beschreven, maar drie minuten irrigeren per wortelkanaal wordt in de praktijk als erg lang ervaren. Uit de uitkomsten van het tweede onderzoek (hoofdstuk 10) bleek dat wanneer bij de continue stroom de irrigatietijd werd verkort van 3 minuten tot 1.5 minuut er significant minder dentine uit het wortelkanaal werd verwijderd ($p=0.017$). Indien bij de intermitterende flushtechniek de irrigatietijd wordt verkort van 3 minuten tot 1 minuut blijft de effectiviteit van de PUI gelijk ($p= 0.550$). Waarschijnlijk kost effectieve apicale verversing van de irrigatievloeistof ongeveer drie minuten tijdens de continue flushtechniek. Bij de intermittent flush methode is de verversing effectiever. Bij deze methode treedt er ook meer verwarming op van de NaOCl omdat deze niet gekoeld wordt door de continue instroom in de pulpakamer. Dit geeft een temperatuursverschil van ongeveer 16 °C tussen de irrigatievloeistoffen gebruikt tijdens beide methoden. Deze temperatuursverhoging verhoogt de effectiviteit van de NaOCl.

Natriumhypochloriet blijkt veel effectiver te zijn in het verwijderen van dentinedebris uit het wortelkanaal dan water ($p=0.001$) (hoofdstuk 9 en 10). NaOCl heeft een sterk weefseloplossend vermogen wat nog versterkt wordt als NaOCl verwarmd wordt. Dit zou voor een deel dit verschil in effectiviteit kunnen verklaren.

De conclusie die getrokken kan worden uit beide hoofdstukken is dat de continuestroom methode en de intermitterende flushmethode twee verschillende irrigatiemethoden zijn met een ander werkingsmechanisme. Bij de continuestroom methode moet de irrigatievloeistof door een actieve akoestische stroming naar apicaal worden getransporteerd om voldoende verversing van de NaOCl te veroorzaken. Dit zal met de huidige ultrasone apparatuur ongeveer 3 minuten kosten. Bij de intermitterende flushmethode is de apicale verversing controleerbaar en effectief en kan de irrigatietijd verkort worden tot 1 minuut.

Calcium hydroxide ($Ca(OH)_2$) wordt binnen de endodontologie veelvuldig gebruikt als tijdelijk vulmateriaal tussen twee behandelzittingen in, als anti-bacterieel middel. Het is echter bekend dat het moeilijk is om $Ca(OH)_2$ weer uit het wortelkanaal te verwijderen. Een complete verwijdering van de $Ca(OH)_2$ is van belang omdat resten die achterblijven op de kanaalwand een negatieve invloed kunnen hebben op de afsluiting van de kanaalvulling. Omdat PUI meer effectief is in het verwijderen van dentinedebris uit het wortelkanaal dan handirrigatie zou PUI ook effectiever kunnen zijn in het verwijderen van $Ca(OH)_2$ uit het wortelkanaal. Zoals in het vorige hoofdstuk is beschreven is NaOCl meer effectief als irrigatievloeistof tijdens PUI dan water. Indien alleen het weefseloplossend vermogen van organisch weefsel hier aan ten grondslag ligt dan zou de effectiviteit van NaOCl en water gelijk moeten zijn daar $Ca(OH)_2$ niet organisch is en niet oplost in NaOCl.

Uit de resultaten van het onderzoek besproken in hoofdstuk elf blijkt dat ook hier water minder effectief is dan NaOCl tijdens PUI in het verwijderen van $Ca(OH)_2$ ($p< 0.001$) en dat PUI met NaOCl effectiever is dan handirrigatie ($p=0.002$). Er was geen significant verschil tussen de handirrigatie en de PUI met water ($p=0.765$). Wanneer deze resultaten werden vergeleken met het verwijderen van dentine debris uit het wortelkanaal, dan bleek $Ca(OH)_2$ moeilijker te verwijderen. Het gemiddelde percentage verwijderde $Ca(OH)_2$ was 63.3% terwijl uit eerder onderzoek gebleken is dat dit voor dentine debris ongeveer 90% kan zijn. Omdat PUI met NaOCl als irrigatievloeistof ook effectiever is dan PUI met water tijdens het verwijderen van een niet organische stof uit het wortelkanaal moeten andere mechanismen dan het verschil in weefseloplossend vermogen of de stijging van de temperatuur hieraan ten grondslag liggen. Het blijkt dat er in oplossingen van zouten tijdens ultrasone stimulatie een ander soort bellen ontstaan dan in water, namelijk meer kleine bellen. Verder heeft gas een invloed op het oscillatiepatroon van de bellen tijdens cavitatie en hier zou chlorine een rol bij kunnen spelen. Uit deze gegevens kan geconcludeerd worden dat NaOCl een meer effectief stromingspatroon geeft tijdens PUI en dat dit wordt ondersteund door kennis uit de fysica. Welke factoren hier precies een rol in spelen en hoe is nog niet bekend.

Om te beoordelen of PUI ook effectiever pulpa weefsel uit ovale wortelkanalen verwijdert dan handirrigatie is de studie uit hoofstuk 12 ontworpen. In ondermolaren werd direct na extractie het mesio-buccale kanaal chemo-mechanisch gereinigd. Eén groep ontving PUI als laatste irrigatie, de andere groep handirrigatie. De mesio-linguale kanalen waren de controle voor de mesio-buccale kanalen. De irrigatietijd en het volume van de irrigatieoplossing waren gelijk voor beide groepen. Doordat de instrumentatie en de irrigatie direct na de extractie werden uitgevoerd had het pulpaweefsel dezelfde structuur als bij een in vivo situatie. Na de behandeling zijn de kanalen gevuld met een 10% formaline-oplossing om de kanaalinhoud te fixeren. Op 2 en 3 mm vanaf de apex zijn vervolgens coupes gesneden en deze zijn toen gekleurd met een hematoxiline eosine kleuring. Daarna is de hoeveelheid debris in de wortelkanalen gemeten. In de groep geïrrigeerd met PUI was 3.2% debris aanwezig in het wortelkanaal en in de handirrigatie groep 23.2%. Dit verschil was significant ($p<0.001$).

De conclusie van dit onderzoek is dat PUI meer pulpaweefsel en dentine verwijdert uit het wortelkanaal dan handirrigatie. Gezien de resultaten uit het laatste onderzoek kan welhaast de conclusie getrokken worden dat ook in vivo PUI effectiever zal blijken dan handirrigatie.

Een proefschrift komt natuurlijk altijd tot stand met de hulp en medewerking van velen die ik hier zeer erkentelijk voor ben.
Speciaal wil ik mijn ouders noemen zonder wier specifieke eigenschappen ik dit niet had kunnen volbrengen. Met name het optimisme dat ik van mijn moeder heb geërfd is een bijna onuitputtelijke inspiratie bron gebleken. Verder is de liefdevolle steun en toeverlaat van Anco van grote waarde geweest.
Tenslotte wil ik alle medewerkers van de afdeling CEP voor ieders bijdrage bedanken. Mijn speciale dank gaat uit naar alle studenten voor hun hulp bij de diverse laboratoriumproeven. Zonder hun inspiratie, enthousiasme en hulp was dit proefschrift nooit tot stand gekomen.

Curriculum Vitae

Luc van der Sluis werd op 7 mei 1960 in Amsterdam geboren, alwaar hij in 1976 zijn gymnasium B diploma haalde. Daarna studeerde hij tandheelkunde aan de Universiteit van Amsterdam en ontving hij in 1985 zijn tandheelkunde bul. Na zijn militaire dienstperiode en de eerste werkervaringen die hij in Italië opdeed startte Luc in 1990 de post academische opleiding endodontologie aan de ACTA die hij in 1993 afronde. Sindsdien is hij in deeltijd bij de afdeling CEP werkzaam gebleven. De eerste 10 jaar heeft hij zich voornamelijk met het keuzeonderwijs bezig gehouden. Daarna is hij steeds meer onderzoek gaan doen en geeft hij tevens postacademisch onderwijs. Naast het ACTA is Luc als tandarts-endodontoloog verbonden aan de Verwijspraktijk voor Tandheelkunde Amsterdam. Verder verleent hij zijn medewerking aan de NVvE en is Luc sinds kort mede hoofdredacteur van Endodontic Practice Today. Al die jaren is hij trouw gebleven aan zijn passie voor barokmuziek en het spelen op de traverso.