University of Birmingham

School of Dentistry

A Comparison of Rotary and Reciprocating Nickel Titanium Preparation in Simulated Root Canals

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Abstract (not to exceed 200 words - any continuation sheets must contain the author's full name and full title of the thesis):

Aim
To evaluate simulated root canal preparation using two different preparation techniques – classical ProTaper and reciprocating. Operators prepared resin blocks which were either uncovered or covered.

Methodology
Inexperienced operators were used to prepare simulated canals with ProTaper nickel titanium rotary files using an electric motor in both the classical ProTaper sequence of four files in a continually clockwise rotating action, and in a reciprocating clockwise and anticlockwise fashion using only one file from the ProTaper sequence - the F2. Canals were either covered with tape to obscure vision, or left uncovered. Photographs were taken of the canals before and after preparation, and the images superimposed for comparison. The canals were evaluated against the five requirements of root canal shape described by Schilder in 1974.

Conclusion
This research demonstrated that the classical ProTaper technique of four files was more likely to produce a preparation meeting Schilder's criteria for ideal mechanical shaping of root canals when compared to the reciprocating technique using one file. It also demonstrated that when the resin blocks were covered, it was more likely that a canal preparation would meet Schilder's criteria for ideal mechanical preparation of root canals than if they were uncovered.

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I dedicate this work to my wife, Claire, and our beautiful daughter Abigail. Words cannot express my thanks and gratitude for the strength that their endless and unwavering love, support, help and encouragement have given me. Claire, you are an amazing person, and I love you both so much.

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PART TWO

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1 Introduction

1.1 The Natural Tooth and the Disease Process

A tooth has a network of blood vessels and nerves that enable detection of thermal changes, regulate biting, and supply all the nutrients needed to maintain vitality. This network exists in a space inside the tooth that is free from bacteria and is walled off from the mouth by the surrounding tooth structure. Bacteria can enter this space if, for example, there is a fracture in the tooth or if decay exists that penetrates the tooth to a sufficient depth. There then follows an inflammatory reaction, often resulting in severe pain. As more bacteria enter the space, and the bacteria utilise the remnants of the tissue as food, an infection develops resulting in an abscess. The tooth only has a very limited blood supply, and is not able to defend itself well from the bacterial attack, and so often soon after the bacteria enter, the tooth dies and an abscess forms.

1.2 Root Canal Therapy and Instrumentation

A patient who presents in pain has two main options: either the removal of the tooth by extraction, or treating the pain by cleaning out the infection from within the roots by a treatment called root canal therapy.

The goal of root canal therapy is the removal of bacterial infection from within the root canal system, or the prevention of such an infection becoming established. To do this the root canal must first be accessed and then cleaned and shaped. Cleaning and shaping is performed by a combination of mechanical removal of the infected and non infected root canal tissue, as well as some dentine from the root canal wall, and chemical disinfection by removal of bacteria and their products from within the root canal space.

Root canals are rarely straight and have a varying degree of curvature along their length, hence the instruments used when cleaning and shaping them can become stressed as the degree of curvature increases. It can also be difficult to access all areas successfully along the entire length of the canal. A successful treatment requires the creation of a smooth, progressively tapered preparation that will facilitate chemical debridement and subsequent filling to prevent re-infection.

The ideal root canal preparation should be instrumented to produce a progressive taper, with the original anatomy maintained; the canal becoming narrower as it goes from coronal (top of the root canal) to apical (end of the canal), with the end of the preparation in its original position and not over enlarged.

Modern root canal treatment involves using stainless steel or nickel titanium files to negotiate and shape the root canals after they have been accessed. This provides access for irrigating solutions to disinfect the canal, and root canal obturation materials to fill and seal the canal when preparation has been completed.

The latest systems use nickel titanium instruments and use either 360 degree rotation or a combination of clockwise and anti-clockwise movement to prepare the canals. There are numerous rotary nickel titanium file systems available, with differing designs in terms of their taper and flute design. All root canal files are now designated as single use instruments as they must be discarded after treatment is completed on a patient. This has encouraged manufacturers to investigate how they can produce file systems that use fewer instruments to achieve the same end result in terms of shape and therefore save on consumable costs.

This study focuses on two rotary techniques, namely the classical ProTaper technique and the more recently introduced reciprocating technique. Both use nickel titanium files to shape the canals. The key differences are the classical ProTaper technique uses a continuous rotation and requires four files, whereas the reciprocating technique uses just one file and non continuous rotation.

1.3 ProTaper

The classical ProTaper system uses a 'crown down' way of preparation where the bulk of dentine is removed initially from the top and middle parts of the root before progressing to the end. ProTaper instruments have a triangular cross section. Their design minimises contact between the file and the canal, and so decreases the load when it is cutting, and increases the efficiency. The angle and pitch of the cutting blade continuously changes along the length of the cutting flutes to ensure effective dentine removal, and stops the file being pulled and screwed into the canal.

ProTaper instruments are grouped into Shaping and Finishing files. The Shaping files are used first and have a small diameter at the tip, along with a narrow taper which then increases as distance increases from the tip. This results in the tip of the file not being active, but acting to guide the body of the instrument along the canal path. This minimises the chance of file fracture, as it results in the strongest and most efficient part of the instrument performing the active cutting. The Shaping files are designated S1 and S2 and are responsible for shaping the upper and middle parts of the canal. The Finishing files have a fixed taper for the last 3mm of the file which shapes the apical end of the root canal. The taper of the file then reduces from 3mm to the coronal end which means most of the cutting is done in the apical third. There are a number of Finishing files available, of which the ones used in this research were the F1 and F2 (these are described in Chapter 4, page 89).

1.4 Reciprocating Technique

The reciprocating technique uses the F2 Finishing file from the ProTaper sequence to both shape and finish the preparation after negotiation with hand files. The file is used in a handpiece with a reciprocating action where the clockwise and anti-clockwise movement is timed rather than dictated by the degrees of rotation. The method is therefore simpler than the classical ProTaper system, with the great advantage of cost saving because only one file is used.

1.5 Aims of the Study

The primary aim of this study is to assess whether the simpler, cheaper, reciprocating technique is as effective as the classical ProTaper technique for canal shaping when evaluated against the requirements of root canal shape described by Schilder in 1974, namely:

1. Original anatomy maintained
2. The canal gets narrower as the canal progresses to its terminus
3. The canal has a continuous smooth progressive taper
4. The end of the canal must be in its original position spatially and has not been moved or transported
5. The end of the canal must be as small as practical and not over enlarged

In this study, the preparations were also assessed to see if they had been over-prepared coronally, over-prepared apically or ledged.

The differences between the two different preparation techniques were assessed using simulated root canals which were either unmasked, and so the operator could see the canal, or masked with tape to prevent the operator seeing the canal. Masking the canals was done to more realistically recreate the conditions clinically, where the operator must rely on tactile feedback and two dimensional pre treatment images of the canal to complete instrumentation.

In summary, therefore, this work had two objectives:

- To evaluate two root canal preparation techniques: rotary and reciprocating.
- To establish if covering the block affected the quality of canal preparation compared to where it was uncovered.

2 Endodontology

2.1 Gross Anatomy of the Tooth, Structure and Function

The tooth consists of two parts – the crown and the root (Torneck and Torabinejad 1996). Inside it lies the root canal which contains the dental pulp. The area where these two parts meet is called the cervical margin. The crown is covered in a very hard, highly mineralised substance called enamel, which is made up of a crystalline structure of prisms joined together by a substance similar to the prisms, but aligned differently. The name of the cell responsible for the production of enamel is an ameloblast. It exists when the enamel is formed on the surface of the tooth, but is lost when the structure is complete. This means that the enamel is a non-vital substance with high strength characteristics that cannot reform if the structure is damaged and broken down as it is in tooth decay. The layer inside the enamel is called dentine and is less mineralised. It forms the bulk of the tooth, has a tubular structure, and is laid down by cells called odontoblasts. It is a vital, rather than non-vital structure, and is responsible for detecting thermal changes due to fluid being present in the tubules, which moves when air is moved past them. This stimulates receptors at the base of the tubules resulting in pain (Brännström 1986). Dentine also has a repair capability. The tubules extend from the enamel to the nerves and blood vessels inside the tooth, which run in the anatomic space we refer to as the root canal. This space is surrounded by dentine and houses the pulp. The diagram overleaf shows the structure of the tooth.

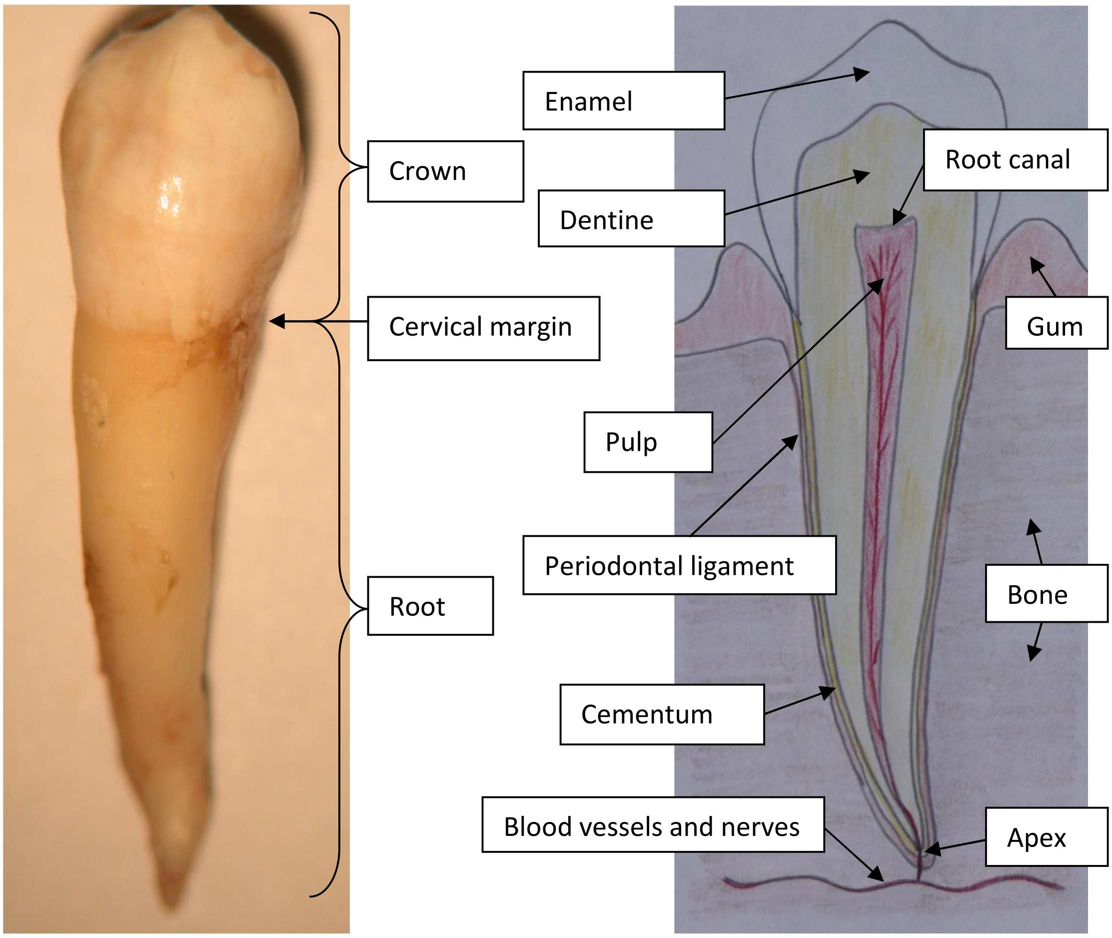

Figure 1: External and internal tooth anatomy

The pulp is thought of anatomically as a separate entity from the enamel and dentine, but in fact has the same cells present as dentine and the two are referred to as the pulp-dentine complex (Orchardson and Cadden 2001). The pulp is responsible for the repair and laying down of new dentine when stimulated to do so, and contains blood vessels, nerves and connective tissue. Its initial role is the development of the tooth and its structure. When the tooth is fully formed its role is maintenance, protection and nutrition.

The tooth is joined to the surrounding and supporting bone by the periodontal ligament. It is a connective tissue which has a shock absorption and sensory role. The periodontal ligament is made up of a collection of fibres which are continually changed and re-modelled in their formation to accommodate any load placed upon them by the tooth in function. The fibres attach to the surrounding bone at one end, and into a material called cementum at the other. Cementum covers the root part of the tooth and is adhered to the dentine. It has no blood supply and is less mineralised than the surrounding dentine.

2.2 Tooth Development

Tooth development begins from the sixth week *in utero* to the fifth year of life. The pulp originates from cells called ectomesenchymal cells. These cells originate from the neural crest in the developing embryo. The ectomesenchymal cells differentiate into the cells of the enamel and dentine – ameloblasts and odontoblasts (Ten Cate 1994). The ectomesenchymal cells aggregate at specific locations where the teeth will eventually be. These cells form the dental papilla, which will eventually give rise to the dental pulp. Tooth development begins with a pinching of the epithelium of the upper and lower developing jaw. This gives an organ that changes shape as development progresses. The following diagram (Trowbridge and Kim 1998) shows this change.

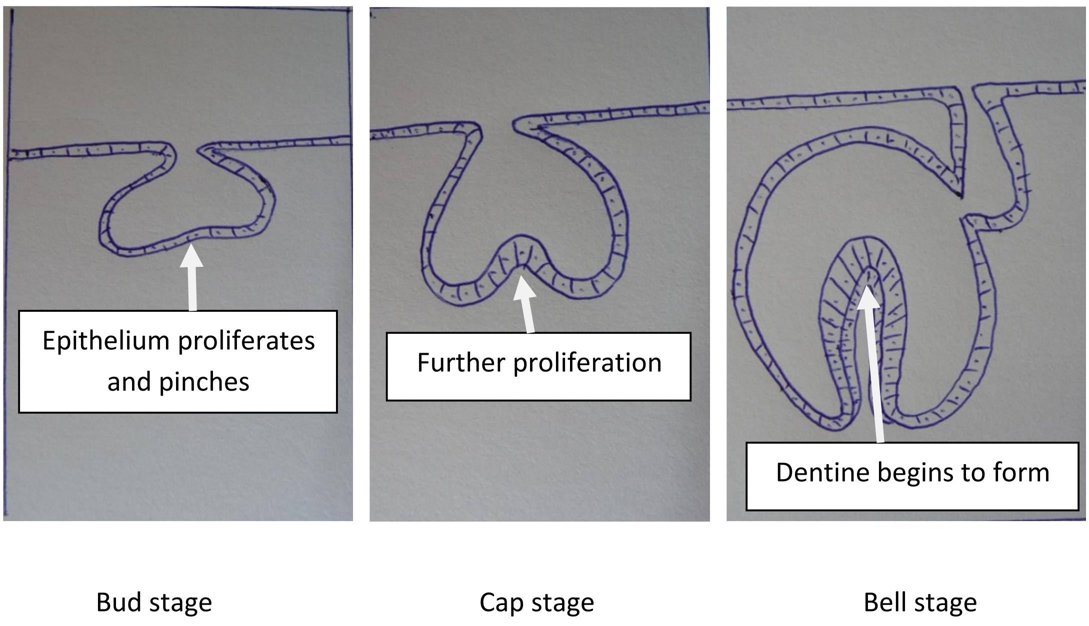

Figure 2: Tooth development

As time progresses, the epithelium takes on a more tooth-like shape. At the last stage the cells differentiate into ameloblasts and odontoblasts. The enamel and dentine is then laid down. Dentine is laid down first, but matures at a slower rate than enamel. The root then develops after the enamel has been formed. In the root, the first cells are odontoblasts, which lay down the root dentine, followed by cementoblasts, which produce cementum. As the root develops, the epithelium grows downwards and encloses the dental papilla, which eventually gives rise to the pulp. The epithelium does not entirely meet, but retains a small opening or foramen at the end of the developing tooth. It is this apical foramen that is the anatomical part where the root canal ends, and where nerves and blood vessels enter the tooth.

2.3 The Anatomy of the Root Canal

The pulp cavity contains two main parts, which are the pulp chamber and the root canals. The first emergence of the pulp is the pulp horns, which are commonly located under the cusps of the tooth (Wilcox and Walton 1989). Further removal of the central part of the dentine will reveal the pulp space known as the pulp chamber. The shape of this area is very variable, and can change in response to age and external forces such as decay, which will be described later. The entrances to the root canals are located at the base of the pulp chamber (Krasner and Rankow 2004) and are referred to as the canal orifices. This is the first part of the root canal.

The diagram overleaf shows access to the entrances of root canals at the base of the pulp chamber.

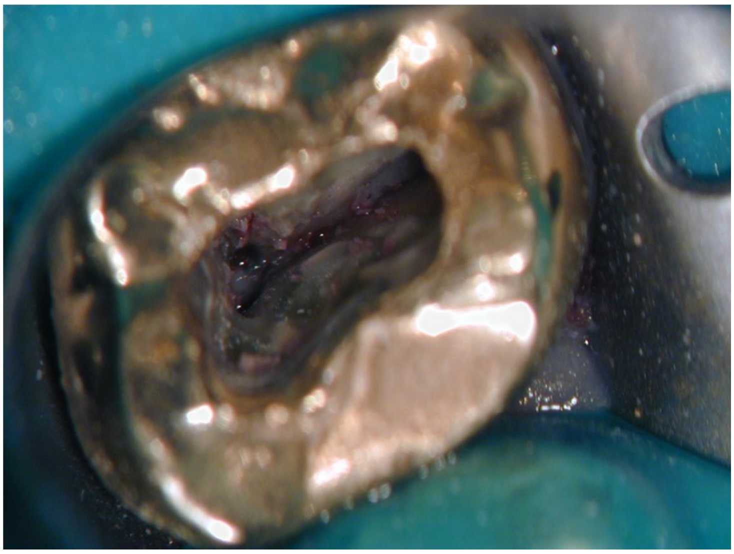

Figure 3: Molar tooth with a gold crown with access to the pulp chamber. This has been performed by drilling a hole in the crown and then removing dentine centrally

All root canals have varying anatomy. In the 1920s Hess and Zurcher demonstrated this by injecting vulcanite rubber into the pulp spaces of teeth and demineralising the surrounding calcified tooth tissue (Hess and Zurcher 1925), as shown in Figure 4, below.

Figure 4: Root canal anatomy (Hess and Zurcher)

In an ideal situation each root would contain one round canal centred within it that tapers from its entrance to the end. Unfortunately this is almost never the case. Roots can have multiple canals that are interconnected by fine branches that cannot be easily located (Vertucci 1984). They have small areas that branch off the central root called fins and deltas, rather than the continuous taper of the ideal anatomy. Features of the root canal system include accessory (or lateral) canals, furcation canals, connections and foramina.

The small branches that extend away from the main canal are accessory or lateral canals and most commonly occur in the apical third region of the root canal. They can occur at any range of locations along the length of the canal due to irregular development of the root. They are a source of connection from the main root canal to the external root surface, and so connect periodontium to pulp. Furcation canals occur on the floor of the pulp chamber above the level of the canal orifices. Accessory or furcation canals often exit at distant locations from the main exit and have their own foramen.

Figure 5, overleaf, contains a series of images of the internal anatomy of a root from a first molar tooth produced using microcomputed tomography (images courtesy of Jonathan Robinson), showing the extent of the interconnections and varying anatomy of the pulp.

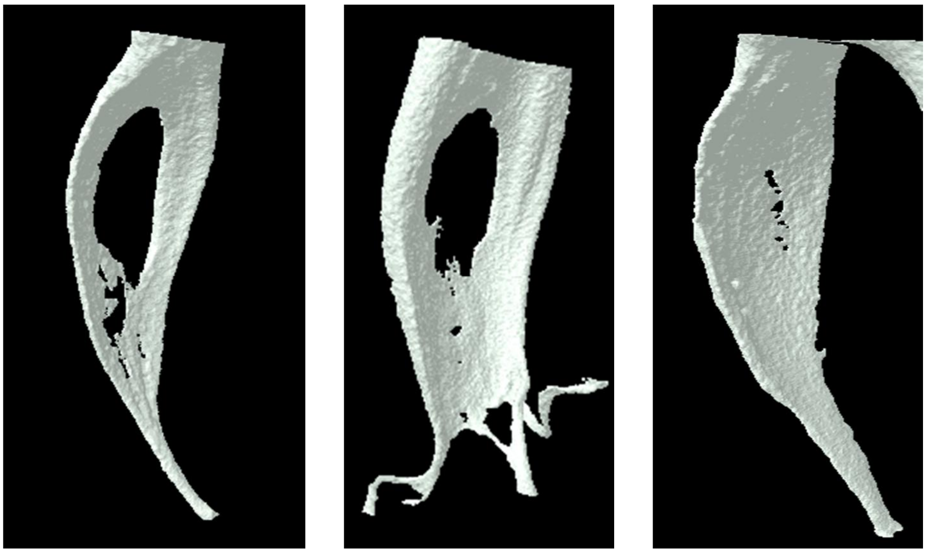

Figure 5: The internal anatomy of a molar root

The end of the root is called the apex. The exit of the root canal varies in shape and size and is referred to as the apical foramen. It is not circular and is not necessarily located at the end of the root. Anatomically the foramen is positioned an average of 0.5 - 0.75mm from the end of the root (Kuttler 1955) (Ricucci 1998) (Ricucci and Langeland 1998) (Gutiérrez and Aguayo 1995).

Most canals have a degree of curvature which is generally fairly gentle, but can be severe. This obviously has an impact on the shape of the final preparation. The greater the curvature, the more difficult access can be to the apical part of the canal system.

The root canal may be thought of as being similar to a tree with a central trunk with interconnecting branches coming off it. Sometimes there is one main trunk, but there may be more than one, which may or may not connect with the other. There are varied numbers of root canals within the root. Different teeth have more common configurations which are vital to understand, but these are only a guide, as anatomy varies greatly.

Attempts have been made to define and categorise the anatomy by a number of authors. The most widely used systems of classification of the shapes of the internal anatomy were described by Weine (Weine *et al* 1988) and Vertucci (2005). The Weine classification is less complicated than that of Vertucci and is more readily used when discussing canals shapes, as can be seen in the diagrams overleaf.

Weine classified root canals as follows:

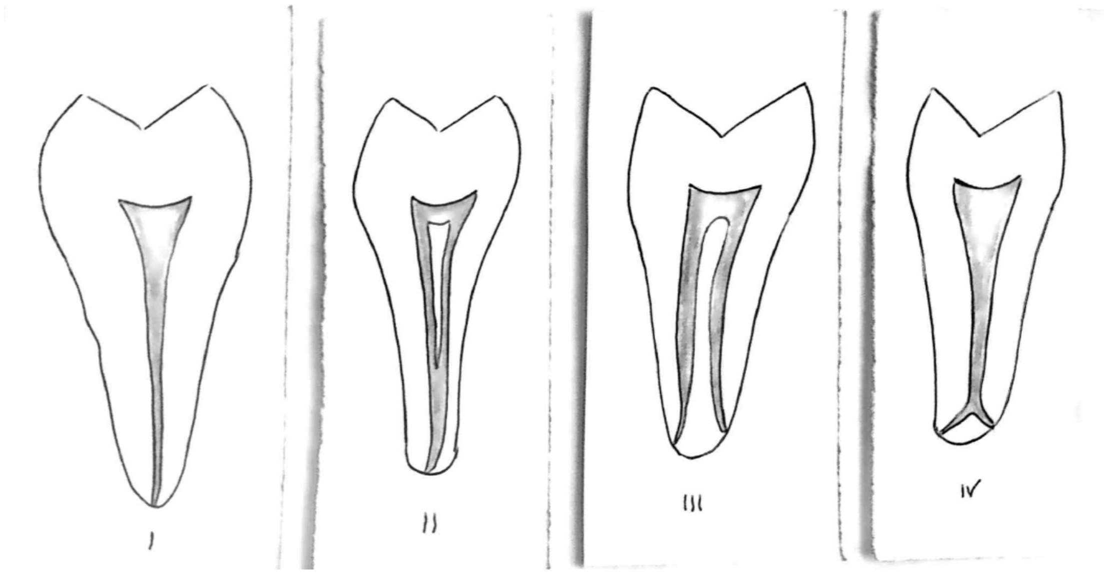

Figure 6: Weine classification (Lumley et al *2006)*

Vertucci classified root canals as follows:

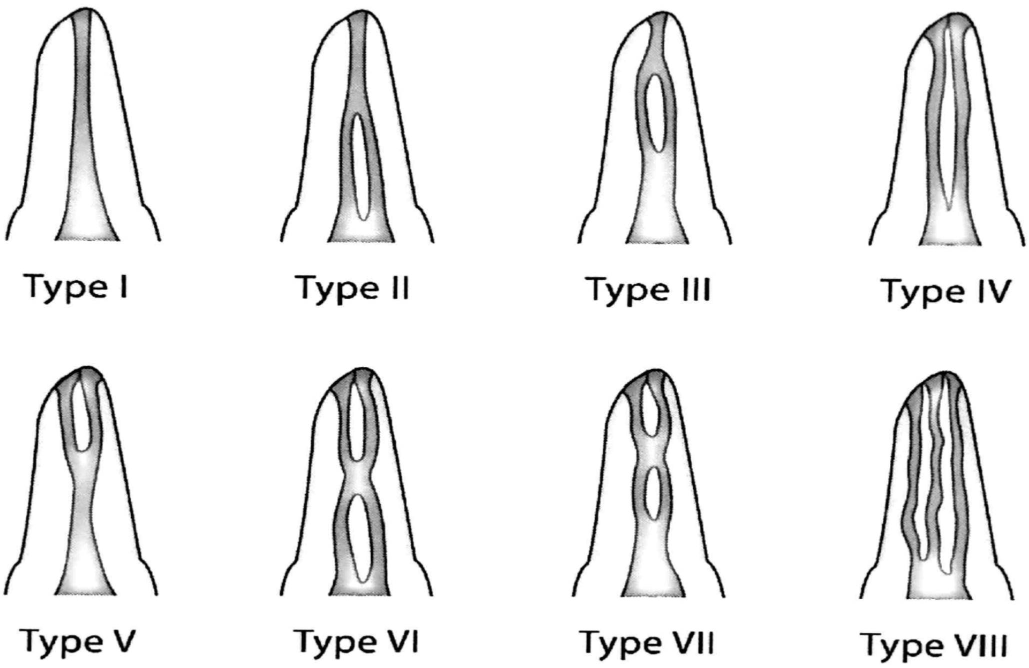

Figure 7: Vertucci classification (Vertucci 2005)

2.4 The Pulp and its Contents

2.4.1 Pulp

The pulp is a connective tissue. It consists of cells, ground substance and neural and vascular supplies. It is encased in a hard tissue called dentine. The dentine is also a connective tissue laid down by cells called odontoblasts. There are different types of dentine (Trowbridge and Kim 1998). The first, primary dentine, forms during tooth development. It lies between the pulp and the enamel and is the most prominent type. Secondary dentine is formed after root development is complete and is produced slowly throughout the life of the tooth. It is similar in structure to primary dentine, and is laid down circumferentially around the pulp chamber, resulting in the latter becoming progressively smaller with age. Tertiary or reparative dentine is formed in response to external stimuli such as decay and bruxism (tooth grinding). It is formed more quickly than other types and so has a more irregular pattern and structure. The role of the pulp is dentine formation and defence (Torneck and Torabinejad 1996). In terms of defence the most important aspect is when the pulp is invaded by bacteria, especially from tooth decay. The pulp reacts to bacterial presence by inflammation and by laying down reparative dentine. This helps to maintain and protect the tooth. It serves to wall off the advancing bacteria and prevent infection becoming established within the pulp.

The pulp also has a blood supply. Large arterioles from dental arteries enter the tooth via the apical foramen, with smaller vessels entering via minor foramina (Trowbridge and Kim 1998). As the vessels emerge coronally, more and more branches extend, giving a complex network of capilliaries in this area. The blood drains away from the pulp via venules of similar proportions to the arterioles having been collected from the capilliaries, and exits down the centre of the canal to the outside vessels. It is this supply that allows some defence ability. Low level inflammation is dealt with by confining and eliminating bacteria, but larger infiltrations cause strangulation of the blood supply leading to loss of the supply and subsequent death of the tooth.

2.4.2 Nerves

There are a number of types of nerve tissue within the pulp (Narhi 2003). The most important are "*A δ* (delta)" and "C *fibres"*. The A δ fibres are responsible for the short sharp pain felt with cold air or drilling the tooth. These fibres are stimulated when fluid which is contained within the dentinal tubules is moved through capillary action. This can occur when the tooth is dried, or exposed parts of the dentine are touched by a dental probe, for instance.

C fibres are responsible for the dull aching sensations that persist for a longer period of time and indicate pulpal damage. They respond to thermal stimuli and are located deeper within the pulp. They have a higher threshold than the A δ fibres and so there needs to be a higher stimulus to cause them to be activated. There is a third type of fibres called "β (beta) *fibres*", which are involved with the regulation of loading on the tooth.

When vital, the pulp is protected by the dentine and enamel around it. However, if this is breached, the bacteria and the substances that the bacteria release damage the pulp and cause inflammation (Cadden 2001). Bacteria gain access through dental caries, fractures into the dentine or pulp, or via accessory canals which become exposed due to periodontal disease. The oral cavity contains hundreds of bacterial types, but only a percentage of these have been isolated from cultures of infected root canals. These cultures mature as time progresses within the root canal, with the number and type of bacteria varying as a biofilm develops. Biofilms are defined as complex collections of micro-organisms attached to a surface (Siqueira Jr. 2008), which is in this case the internal wall of the root canal. Within the biofilm there are numerous types of bacteria that exist in their own ecosystem, with the organisms having specific functions within that community (Svensäter and Bergenholz 2004).

The entry of bacteria causes a reaction by the host. The first reaction is local inflammation and later a laying down of reparative dentine. The severity of the attack determines the outcome, with healing occurring within three to eight weeks.

Bacteria exist in decay, but most importantly are involved in microleakage. This is when bacteria leak through an old or poorly completed filling. The bacteria diffuse along the dental tubules to cause inflammation which can be blocked in a healthy pulp, but not in an unhealthy one. Inflammation leads to an early lesion which results when toxins and inflammatory mediators are carried periapically. When the pulp loses vitality it has no defence against the bacteria, and so is overwhelmed. The next area of defence is at the periapex, outside the tooth, where there is a good blood supply. The body here has to wall off the infection and attempt to contain it within the root canal.

Bacteria from within the oral cavity are those almost exclusively isolated from within the root canal (Figdor and Sundqvist 2007), but their composition and proportions within this environment are very different to that of the oral cavity. Root canal infections can contain ten or more different bacterial species with three to four being the most prevalent (Gomes *et al* 2004).

The periapical zones of Fish (1939), was an attempt to explain the rationale for infection and the interaction of the periapical tissue and bacteria. The zones were as follows:

A - Zone of infection: This is the zone immediately in contact with the tooth. In this area there are toxic products which have been released by the micro-organisms. Cells called Polymorphonuclear (PMN) Leucocytes are present in great numbers, indicating the site of infection.

B - Zone of contamination: In this zone, toxins from the zone of infection are present and prevent survival of normal cells. The cells which are present are cells of body's defence, along with toxins, lymphocytes and plasma cells.

C - Zone of irritation: This zone contains a more dilute concentration of toxic matter which is an irritant. Cells can survive though in this area. The cells present are macrophages and osteoclasts which destroy surrounding tissue including bone resulting in resorption.

D – Zone of stimulation: In this zone, the toxins are mild enough to act as a stimulant rather than an irritant. It is a constructive zone and contains fibroblasts and osteoclasts to help repair and regenerate surrounding tissue including bone.

The size of the area of bone resorption and destruction depends on the balance between infection and the host defence (Nair 1997).

2.5 The Changes Associated with Age and Time

When the tooth is formed, the role of the pulp is maintenance, protection and nutrition. With age, the structure of the tooth changes, and the space inside the tooth responds to various attacks from such things as decay and tooth grinding by laying down more dentine in an attempt to wall the pulp off in response to inflammation or bacterial ingress. This means that the internal shape of the root canal is constantly changing, (Bernick and Nedelman 1975), and usually the root canal space is getting smaller with time (Torneck and Torabinejad 1996).

As the tooth ages, or as irritants are exposed to it such as bacteria, this has an effect on the pulp. It can also have an effect on the tooth tissue. Calcification can result. This presents in the form of pulp stones which can occupy the pulp space (Goga *et al* 2008), and can also cause the laying down of dentine by odontoblasts. This can cause the pulp space to reduce in size, which can make location of root canals very difficult.

2.6 The Diseased Tooth - Causes and Progression

For a problem to occur in the pulp, there has to be an inflammatory reaction (Yu and Abbott 2007), which is normally in response to irritation. Irritants include overheating the pulp when preparing a tooth cavity or crown preparation, chemicals in restorative materials, and direct exposure through trauma. The pulp is subject to a number of sources of irritation of which the main one is microbial irritation especially through dental decay and microleakage (Haapasolo *et al* 2005). Bacteria include *streptococcus, lactobacillus, actinomyces, prevotella* and *neisseria* types (Nair 1997) (Sundqvist and Figdor 2003). The initial inflammatory response often occurs before the decay has physically reached the pulp. Bacteria release toxins into the tubules in the dentine, which trigger the inflammatory cells in the pulp. The first cells to respond are called macrophages, lymphocytes and plasma cells. As the decay reaches the pulp, the reaction becomes more intense, and the number and type of cells can change. An acute inflammation occurs and polymorphonuclear leukocytes infiltrate the area where the bacteria invaded the pulp. This area is colonised by bacteria and may become necrotic. This is where the pulp dies, and the space is taken over by bacteria rather than the blood vessel and nerves which cannot respond enough to repel the bacterial advance. When the pulp has been invaded, it is not able to eliminate the bacteria from within it. The speed by which the reaction continues is due to the pulp response in terms of its own defence, and how severe the attack is in terms of the number and virulence of the bacteria involved. The pulp itself is enclosed, and so has a poor blood circulation and therefore poor defence capability. This makes it unlikely that the pulp can survive a bacterial attack, and often the speed at which it progresses is all it can change. Eventually bacteria and bacterial products take over the space, and eventually will spread through the periapical tissue outside the tooth having escaped the confines of the root. This is the cause of dental abscesses, and gives rise to changes in the bone which can be seen on radiographs.

Proof that bacteria have a vital role in the cause of inflammation was demonstrated by Kakehashi *et al* (1965). In this paper, the pulps of 36 rats were exposed to the environment for 42 days. One group of rats were normal and the other was germ (bacteria) free. The germ free rats did not develop abscesses and had only minimal inflammation. The pulps also remained vital and dentine repair was evident. The normal rats had necrotic pulps with some abscesses evident. Some of the pulps in these rats had vital tissue at the end of the root, but no repair had been demonstrated. This proved that it was the bacteria of the normal rats that was the differentiating factor, and without these bacteria, even though the pulps were exposed, no lesions developed.

In a paper by Moller *et al* (1981), the pulps were removed from 78 monkeys. A portion were kept germ free, and the others were infected intentionally with bacteria and then the canals sealed. The non infected canals produced no inflammatory reactions, whereas the infected ones did. The non-infected canals showed no evidence of hard tissue damage and, in fact, again as Kakehashi's paper (Kakehashi *et al* 1965) demonstrated, there had been some dentinal bridge formation. The infected pulps had up to fifteen strains of bacteria in them. 47 out of 52 had radiographic changes indicating mature infections, and some hard tissue damage was evident.

An early theory was described by Rickert and Dixon in 1931 called the hollow tube theory. It described how when hollow tubes were inserted into the skin of rabbits, inflammatory changes persisted. When this was done with solid rather than hollow tubes, no inflammation existed. These experiments were refined by Torneck in 1966 and 1967. He demonstrated that if the implanted tubing was sterile, then no increased inflammation resulted, but if there were micro organisms present, as in the case of an infection, then inflammation occurred. The relevance here to endodontics is that a tooth is in effect an inert sterile tube with the pulp within it, and if this becomes infected then this results in an inflammatory reaction.

The number and type of bacteria appears to change with time and conditions. At the onset the initial bacteria are mixed, with bacteria that can tolerate oxygen but do not require it, called facultative anaerobes, and those that thrive without it called obligate anaerobes. Up to 90% of the infection at the onset is made up of facultative anaerobes (Fabricius *et al* 1982). With time the number of facultative anaerobes decreases compared to obligate anaerobes (Figdor and Sundqvist 2007). It appears that some bacteria also need other types of bacteria to exist, and that the proportions of bacteria will establish their own levels in harmony with each other. This has been proven when different concentrations of bacteria have been introduced into canals, and the proportions re-examined later. In one study (Fabricius *et al* 1982), infections were examined prior to changing the bacterial concentrations, and re-examining later. It was found that the concentrations had returned to their previous levels, suggesting a synergistic relationship that exists to help one another. As time progresses, the environment inside the canal changes, and so the bacterial concentrations and types change as they are better suited to the conditions.

The type and concentration of bacteria also change from the pulp roof to the end of the tooth (Shovelton 1964). Often there are more bacteria in the part nearest the pulp chamber than at the apex, although in one paper 50 strains of bacteria were isolated from root canals in the apical 5mm of infected teeth (Baumgartner & Falkler 1991).

2.7 Dental Pain

How bacteria infiltrate the pulp and cause abscesses has been described. Pain is caused by the release of chemical mediators released in response to initial inflammation (Narhi 2003). Increased pain occurs as the inflammation becomes more severe. The nature and type of pain changes as the inflammation progresses. Often the final stage of pain is when there is an abscess present and the bacteria and their products have escaped past the end of the tooth into the surrounding tissues, although an abscess does not always produce any pain at all. There is obviously a range of types and causes for dental pain, and therefore different requirements in its management (Rosenberg 2002). Initial inflammation can cause slight pain to hot and cold substances and can be associated with some tenderness. The pain is normally short lasting and sharp (Gluskin *et al* 1998). The treatment here is to remove the sources of irritation. This may be some decay, or may be due to an old filling no longer sealing the tooth effectively. The inflammation at this stage is thought to be reversible, and if the source of inflammation removed, then the pain resolves. However, if the bacteria have reached the pulp, then the resulting pain can be different. Pain here is more severe in nature. It lasts longer, may be spontaneous and radiate making it difficult to detect where it originates from. Pain may be made worse by hot substances and relieved by cold ones. This type of pain is irreversible, and requires different treatment. Pain killers that are anti inflammatory can help, but sometimes make little difference. In this instance the only way to treat the situation is to remove the pulp where the bacteria and inflammation are, or extract the tooth, to remove the source of irritation. Antibiotics are of limited benefit as the blood supply no longer exists within the tooth, so they cannot reach the bacteria producing the infection. The limited benefit is that of pain control, as they can help to limit the size of the swelling outside the tooth and so reduce pressure on the tissues. As the bacteria take over the pulp space, response to stimuli is lost, but the tooth becomes more tender as the bacteria escape into the peri-radicular tissues. Swelling may also occur as the infection spreads beyond the confines of the tooth. In these cases, an antibiotic may help reduce the infection outside the tooth, but will not affect the bacteria within the tooth, and so the source of the problem remains. At this point, for the pain to be reduced there needs to be drainage of the infection to reduce the pressure that has built up. This can be a very serious problem as the body cannot always deal with the amount of infection. If the infection overwhelms the body's defences, life threatening infections can develop.

2.8 Treatment Options

When a patient presents with pain, an assessment is required of the severity and the cause of the pain. At first symptoms are mild with some thermal sensitivity but no significant pain as there is little bacterial infection. As more bacteria enter, more pain results that often cannot be relieved by analgesics. The pain becomes more throbbing in nature, and tends to keep patients awake. As yet more bacteria enter, the pain may for a brief time seem to ease as thermal sensitivity decreases, but the tooth starts to become tender. As more bacteria are produced, the tooth becomes very tender and again throbs due to pressure produced by the abscess.

Symptoms are produced due to differing problems. At first, the tooth and therefore the pulp is still alive and transmits pain signals which increase with the stimulation of the nerve fibres described earlier. Initially, the inflammation is reversible and if the source of irritation is removed, then the symptoms can resolve. At the point where the patient is in pain for a longer length of time and painkillers no longer are effective, then the pulpal damage is irreversible, and the source of infection has to be removed.

A patient who presents in pain has two main options; either the removal of the tooth by extraction, or treating the pain by cleaning out the infection from within the roots by a treatment called root canal therapy.

2.9 Root Canal Therapy and Endodontics

The aim of root canal therapy is to eliminate bacteria as effectively as possible from the root canal system. A tooth has a network of blood vessels and nerves that enable detection of thermal changes, regulate loading, and supply all the nutrients needed to maintain vitality. This network exists in a space inside the tooth that is free from bacteria and is walled off from the mouth by the surrounding tooth structure. If bacteria enter this space an inflammatory reaction results, often resulting in severe pain. There are also a number of other ways that the nerve can be damaged, such as through excess heat or trauma. These can also result in an initial inflammatory reaction, or may result in the blood and nerve supply being lost with or without the initial pain.

Eventually as more bacteria enter the space, and the bacteria utilise the remnants of the tissue as substrate, an infection develops resulting in an abscess. The tooth only has a very limited blood supply and is not able to defend itself well from the bacterial attack, and so often soon after the bacteria enter, the pulp necroses and an abscess forms.

The role of root canal therapy is to remove bacteria from within the root and enable the abscess to heal and therefore maintain the tooth, thus preventing the need to take it out.

Endodontology is the branch of dental science that deals with the causes, diagnosis, prevention, and treatment of diseases of the dental pulp and their consequences. In 1910 Dr William Hunter gave a speech discussing the serious role of infection in the human body, describing septic infection as the:

> "...*most prevalent infection operating in medicine*"

and,

> "...*a most important and prevalent cause and complication of many medical diseases*".

He claimed that the

> "...*chief seat of that sepsis is the mouth*"

and that,

> *"...gold fillings, gold caps, gold bridges, gold crowns, fixed dentures, built in, on, and around diseased teeth, form a veritable mausoleum of gold over a mass of sepsis to which there is no parallel in the whole realm of medicine or surgery.*" (Reit *et al* 2003).

He claimed that infections from this area spread to other body areas giving rise to disease. Although this initially resulted in the extraction of teeth to prevent infection, it was from this time to about 30 years later that dentists developed techniques and solutions for the elimination of these infections, and so were the pioneers of endodontics as it is thought of today. Other improvements came in 1920 with the development of dental radiology, and the ability to demonstrate from where an infection was arising. Development of pathology and microbiology also enabled detection of which types of bacteria and micro organisms were involved in infections and to what they may be susceptible to enable their elimination.

In summary, endodontics relates to the elimination of bacteria from within the root canal system to enable normal function and structure to be maintained, and so prevent loss of the tooth.

2.10 Current Root Canal Therapy

To treat an infected or chronically inflamed tooth, the contents of the pulp space are removed and the area thoroughly irrigated with chemicals to disinfect it. This is done by accessing the pulp, and using a combination of instruments and chemicals to negotiate, shape, and disinfect from the top of the root canal to the apex. The length of the canal is carefully measured to ensure that the entire canal has been negotiated, and then is prepared using instruments called files that plane the walls to enlarge it and so facilitate penetration of disinfecting chemicals. Following preparation and thorough irrigation, the tooth is filled to prevent bacterial re-infection, and then restored to function.

Figure 8: Same tooth as Figure 3 after removal of the pulp contents and cleaning and shaping of the root canal

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3 Root Canal Therapy

3.1 Introduction

The goal of root canal therapy is to save teeth with compromised pulps by preventing bacterial colonisation or disinfecting previously infected root canal systems. This is achieved using a combination of mechanical debridement using instruments, and disinfection with irrigant solutions, referred to as chemomechanical debridement, before filling with an inert material (Ng *et al* 2008) (Young *et al* 2007).

The mechanical aspect involves the use of files to debride the canal and prepare a smooth sided shape that will both maximise the efficacy of the chemical disinfectants and permit the placement of a filling to seal the space and prevent re-entry of bacteria. The role of files is to plane the internal walls of the root canal, and negotiate to the end of the root to allow irrigants and root canal dressing materials access to the bacteria. However, mechanical preparation alone will not remove all the bacteria within the canal (Bystrom and Sundqvist 1981) (Dalton *et al* 1998). It is the combination of intra-visit irrigation and inter-visit medication that enables effective disinfection.

3.2 Preparation

One of the most challenging and important aspects of endodontics is accessing the root canal system and identifying the root canal orifices. Without good access, the goals of root canal therapy cannot be met, and procedural errors are more likely (Duigou 2004). It has been demonstrated that it is unlikely that any root will contain an easily accessible single straight tapered canal. The existence of accessory anatomy including deltas, fins and accessory canals means that it is impossible to negotiate all of the root canal system with instruments (Bergmans *et al* 2003) (Foschi *et al* 2004) (Peters *et al* 2001) (Vaudt *et al* 2009). This demonstrates the importance of the role of chemicals in disinfection. It also serves to highlight the importance of adequate access to allow chemicals to enter as much of the canal system as possible, and to allow unimpeded access to the straight part of the root so that the operator has the greatest chance of being able to negotiate the more difficult and intricate apical regions.

When accessing the tooth, the first aspect of the root canal system that is entered is the pulp chamber. This chamber can vary in size and shape from large to almost non-existent. The tooth lays down dentine throughout its life circumferentially and at a slow rate. It also produces dentine in response to stimuli such as trauma, decay, operative procedures (cavity preparation and restoration) or bruxism. This reduces the size of the pulp chamber (Bernick and Nedelman 1975), and makes location of the canals more difficult. Calcifications can also occur, referred to as pulp stones (Goga *et al* 2008), which can block the entrances to canals and occlude the pulp chamber. They are almost the same colour as the surrounding dentine, and so can confuse and hinder location of the canals. The orifices to root canals are usually located under the cusp tips of teeth (Krasner and Rankow 2004). The access has to be of an adequate size to enable these canal openings to be found (Wilcox and Walton 1989). This includes completely deroofing the pulp chamber to allow direct visualisation of the canals and the pulp chamber floor. Adequate access requires a straight line route to the first curve of the root canal; this is called straight line access, and allows better instrumentation of the canal (Mannan *et al* 2001).

There is a varied armamentarium to aid location and access to root canals. The use of a rubber dam to isolate and protect the tooth is mandatory (Lumley *et al* 2006). Its main role is in maintaining asepsis by preventing saliva contamination from the oral cavity, but it also prevents inhalation or swallowing of root canal instruments, helps protect the soft tissues of the patient, and improves visibility for the operator. High intensity co-axial light sources may be used to help visualisation of difficult to see canal orifices and detect colour changes within dentine which may indicate where tertiary dentine has been layed down, and therefore where root canals may be. Magnification is also widely used in combination with these light sources in the form of loupes, which are binoculars that attach to the dentist's safety glasses, or surgical operating microscopes that allow a broader range of magnification to facilitate location of the canals (Buhrley *et al* 2002).

Different drills and burs are also available, along with ultrasonic instruments, to allow small amounts of dentine to be removed in a precise and controlled manner to aid location of the openings to the canals, before they are negotiated, cleaned and shaped.

3.3 Instrumentation

The aim of instrumentation is to remove as much of the infected bacterial mass and its nutritional supply as possible from within the root canal system. It aims to remove the infected inner part of the root canal walls where the dentinal tubules can have been penetrated by bacteria (Siqueira *et al* 1996), and enable access for chemicals into the deepest parts of the canal system. It also serves to produce a shape that is conducive to receiving a filling that will effectively seal the prepared and cleaned root canal.

Files are responsible for shaping the canal to provide access for irrigating solutions and root filling materials. Root canal files are manufactured from either stainless steel or nickel titanium and differ considerably in their design. This gives them different properties, and knowledge of this is used in deciding which ones to use in different situations.

An ideal root canal preparation was described in 1974 by Schilder as follows:

- Original anatomy maintained:

  The original shape and dimension of the root canal should be preserved so that the prepared shape mimics the original anatomical form.

- Canal gets narrower as the canal progresses to its terminus:

  The canal must be at its widest at the canal orifice and get narrower as the canal progresses to where it exits the tooth.

- Canal has a continuous smooth progressive taper:

  As the canal progresses from the orifice to the terminus the rate of narrowing is gradual and a smooth shape is produced.

- The end of the canal must be in its original position and not moved:

  The terminus where the root exits is where it was originally and has not been deviated by the misuse of instruments thus altering the anatomy.

- The end of the canal must be as small as practical and not over enlarged:

  The original dimension of the exit at the end of the root canal should not be damaged by making it much larger than its original form. It can be enlarged slightly, but only in respect of the original dimension and anatomy.

3.4 Root Canal Debridement

One of the main goals of root canal therapy is the removal of bacteria and their products or the prevention of infection. To debride a root canal the pulp remnants must be removed as these are either infected and necrotic, or, act as a source of nutrition for bacteria and so increase the likelihood of re-infection. The root canal wall is also prepared and planed as this can contain a high concentration of bacteria, especially in the more coronal and mid root areas (Love 1996).

Debridement is done using chemicals to dissolve the pulp remnants and kill the bacteria, and using endodontic files to remove infected dentine and maximise exposure of bacteria to chemicals by the preparation of the canals.

3.5 Instruments for Canal Preparation

There are many instruments used to prepare root canals. They are broadly broken down into those used by hand and those used in an electric motor and of rotary design.

3.6 Brief History of Canal Instrumentation

Historically the earliest instruments were crude made initially out of watch springs. The first recorded was in 1838 manufactured by Edwin Maynard (Castellucci). Prior to this root canals had been accessed and treated by devitalisation or cauterization and then protected with a dressing.

In 1864 a thin rubber leaf retained by a clamp was used to isolate the tooth (Castellucci) and protect the patient while preparing the tooth. This has evolved into what we refer to as a 'rubber dam', and its use demonstrates the understanding of the role of asepsis in treatment. In 1891 a camphorated chlorophenol was introduced as a medication to sterilize bacteria from within root canals, indicating the understanding of the bacterial origins of endodontic disease (Castellucci). X rays were first used and developed in the late 19th century, and their use along with observations of abscesses at the apices of teeth signalled the beginning of endodontic diagnosis and treatment. A way of measuring the root length was suggested by G V Black in the early 20th century, and endodontics began to be developed. Unfortunately, the focal infection lecture by William Hunter, and a series of claims regarding the probability of apical infections causing other serious illnesses and acting as distant sites of infection halted endodontic research, and resulted in few treatments being carried out, as teeth were extracted to prevent systemic (body system) spread and life threatening illness. This theory continued until it was disproved in the 1940s and 1950s and faith in non vital teeth being retained and not causing problems was restored.

Early files were ground into a barbed shape out of circular wire and were used to remove vital or non-vital pulp remnants. These 'broaches' or 'rasps' were used in conjunction with the de-vitalising chemicals to remove pulp and infected tissue. The next instruments developed were files and reamers, and are still used to cut and machine the dentine on the canal walls, and to enlarge and remove infected pulp and dentine. Reamers and files are most commonly made out of round wire that has been ground to a tapered square or triangular section and twisted to form the reamer or file. Reamers contain less flutes or twists than files and are more flexible in smaller sizes.

3.7 Manufacture of Instruments

Files can be manufactured by either twisting or by machining. Some files are ground out of a circular blank of stainless steel, for example Hedstrom files, rather than twisted, which results in different properties. Such files tend to be very sharp with flutes that efficiently plane at the dentine walls (Schäfer and Tepel 1996). However, they are less resistant to twisting torque forces and so are weaker if used in this fashion and tend to break more easily, but are flexible.

The most common method of manufacture is to grind the blank metal shape and then twist it.

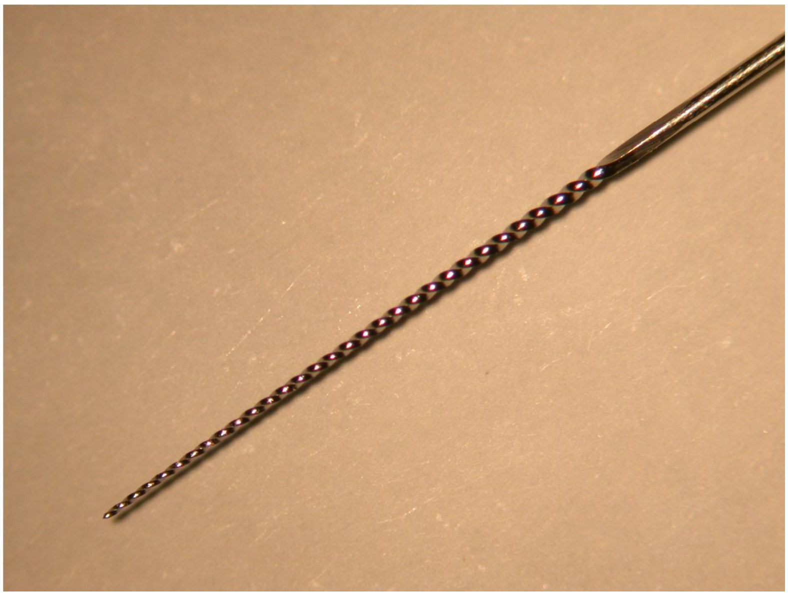

Figure 9: Round wire ground and then twisted to form the file

Different properties can be afforded to the file if the wire is ground to a different shape before twisting. “K Flex” files, for example, are twisted out of a rhomboid metal blank rather than the square blank used to create the ‘k’ file resulting in greater flexibility (Schäfer 1997).

The design of the blank affects how efficiently the file cuts dentine (Molven 1970). The efficiency is dictated by the rake angle of the files' flutes. A positive rake is where, like a wood planer, the cutting blade digs in forwards and actively cuts as it passes over the surface. Files with these characteristics are efficient and remove dentine, but can more easily get stuck as they will lock into the canal wall if screwed in. A neutral rake angle exists where the flutes are at 90 degrees to the tooth surface and cut as they are scratched over the dentine. A negative rake is where the cutting blade is angled away from the direction of cutting (Spangberg 1998).

Manufacturers have now designed files with hybrid qualities by, for instance, grinding or machining files that appear in shape like K files, but have resulting deeper spaces between the flutes to enable more dentine to be removed and the rake angle to be increased. These files will cut efficiently and maintain the canal curvature (Bou Dagher and Yared 1995), but are more prone to fracture as they engage the dentine very easily, and are difficult to pre-curve. An example of this is the "Flex R" file.

The other variable that can affect the ability of the file to enlarge canals is the design of the tip (Miserendino *et al* 1985). Most instruments have a non-cutting tip that is not active. The non-cutting tip is designed so that it will follow the root canal rather than cut and so reduces the incidence of ledges (Tepel *et al* 1995). For some methods of canal negotiation, a modification to the manufactured tip has been recommended which can help to reduce canal transportation (Powell *et al* 1986).

3.8 Stainless Steel and Nickel Titanium

An area that has been more recently explored is the metal used in the manufacture of the files themselves. Stainless steel is the main metal used for hand instruments in root canal therapy. Its advantage over carbon steel is that it is not prone to corrosion caused by the chemicals used in root canals or by steam sterilisation (Eleazer 1991).

Another metal that is now being used and is becoming more prevalent, especially in the manufacture of rotary instruments (which will be described later), is nickel titanium. This is because of the metal's shape memory, flexibility characteristics, and resistance to torsional fracture. (Camps and Pertot 1995). Nickel titanium alloy was initially developed for use in the space program in the 1960s and was called nitinol (Thompson 2000). Its key characteristics were shape memory and super elasticity. This results in a file that does not permanently distort if not stressed past its tolerance, has good strength and a lower modulus of elasticity resulting in flexibility.

Nickel titanium exists in a form called austenite. This is a body centred lattice shape that is stable at high temperatures. As the metal cools, it changes structure and its elastic modulus changes. This is the martensitic transformation. If the metal is again heated it returns to its austenitic state. This is responsible for the characteristic of shape memory. The same thing happens with the alloy when stress is applied. This same transformation occurs from one to the other and back again when the stress is removed. It is this property that is of use in endodontics. The file will spring back to its original shape when stress is removed and so enable treatment of curved canals that may distort or break a traditional stainless steel instrument. Nickel titanium has a recoverable strain of up to 8% versus 1% for stainless steel (Thompson 2000). Nickel titanium files are manufactured by machining rather than twisting the metal blank as is the convention with most stainless steel files.

One of the main disadvantages of nickel titanium files is that they are associated with fracture (Di Fiore *et al* 2006). This occurs when the file is stressed to a greater level than that which causes permanent deformation. Factors influencing this include the speed of file rotation, the curvature of the canal being prepared, and the load put on the file by the operator (Martin *et al* 2003). To safely and predictably use these files, the canal needs to have been negotiated with stainless steel files to ensure a glide path is created prior to their usage to minimise the risk of fracture.

Nickel titanium files are available in a range of tapers and sizes. The tapers are either fixed along the length of the file or variable with multiple tapers.

3.9 Taper

The taper is the rate at which file diameter increases with distance from the tip. Hand files had their taper standardised to ‘02’ according to ISO guidelines (1976)**.** This meant that for every millimetre distance from the tip, the diameter increased by 0.02mm.

A file that has an 02 taper and is a size 20 (0.02mm at its tip) is as follows:

Distance from tip (mm)	0	1	2	3	4	5
Diameter (mm)	0.020	0.022	0.024	0.026	0.028	0.030

Figure 10: Table illustrating 02 tapered instrument diameter along its length

The same tip diameter file with an 06 taper instrument would result as follows:

Distance from tip (mm)	0	1	2	3	4	5
Diameter (mm)	0.020	0.026	0.032	0.038	0.044	0.050

Figure 11: Table illustrating 06 tapered instrument diameter along its length

This radically affects the shape of instruments. The 02 taper instrument would be a lot narrower than the 06 instrument, which has an impact on its usage within the root canal.

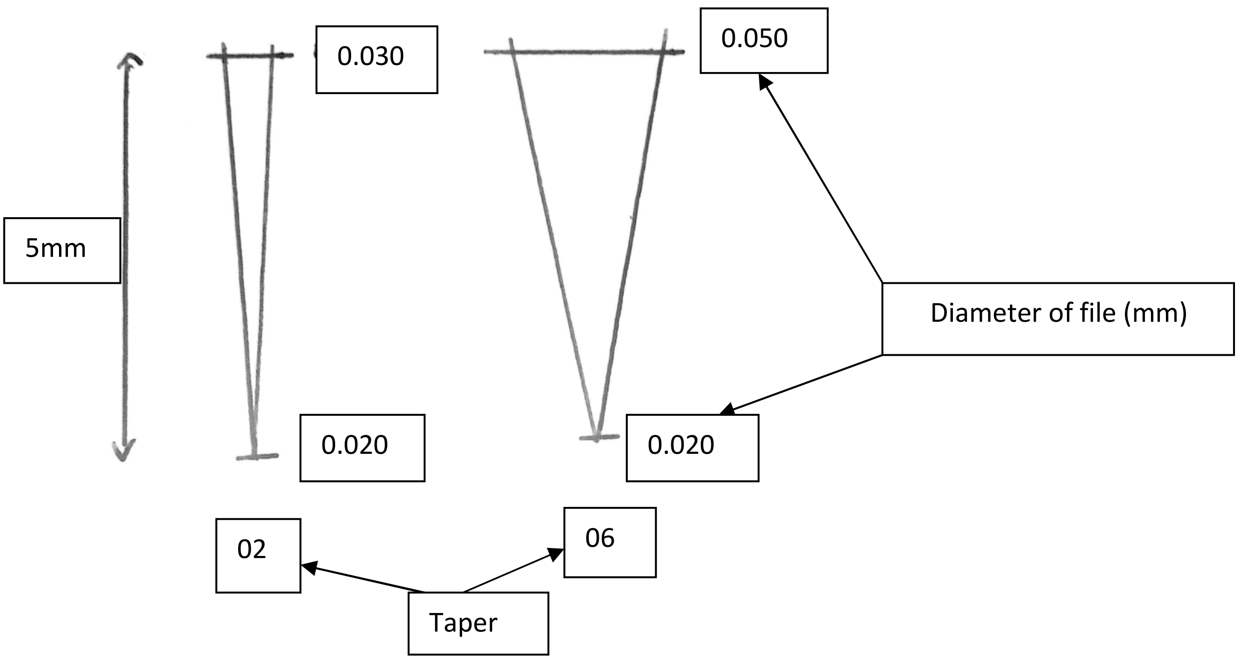

Figure 12: 02 and 06 taper

With the onset of rotary instruments and the use of nickel titanium, different tapers were introduced. Initially these were fixed along the length of the file and ranged from 02 to 12. Files are now available with variable tapers where the taper along the file changes.

3.10 Fracture

The cause of fracture is often too much load applied by the operator (Sattapan *et al* 2000), which in turn increases the torque on the instrument. This results in the tip of the instrument engaging the canal and meeting resistance as it is rotated by the operator in the area where the file is at its weakest. The file fractures as the load imparted by the operator exceeds the resistance of the file. Another cause of file fracture is due to 'taper lock'. Taper lock occurs when a substantial length of the cutting blades of the file engage in dentine (Ruddle 2003). The greater the length of file that is engaged in dentine, the greater the amount of torque required to turn the file. This is a problem with smaller files as the torque required to turn the instrument can be greater than that required to fracture it, resulting in breakage. Fracture can result in a blockage that prevents further cleaning and shaping of the canal, and can therefore result in failure.

3.11 Preparation Methods: Hand Preparation

To prepare root canals hand files can be manipulated in a number of ways. The most common ways of using hand instruments are filing, reaming, watch (or stem) winding, balanced force and rotational.

3.11.1 Filing

Filing uses a push-pull action with an amplitude of 1-2mm to plane the wall of the canal (Saunders and Saunders 2003). The design of the file determines the efficiency of dentine removal in terms of how sharp the cutting flutes on the file are and how actively they cut. The filing motion, if used in one area of the root, can cause a groove and so should be done circumferentially around the entire outside of the canal to evenly prepare it (Wu and Wesselink 2001). The problem with this is that as the canal cannot be visualised, this very difficult to achieve. Another problem is that with the pushing and pulling, dentine is cut, which is then pushed towards the apex of the tooth and so can block the passage of subsequent files to the apex, or push the canal contents out of the tooth into the surrounding tissues (Al-Omari and Dummer 1995).

3.11.2 Reaming and Watch Winding

Reaming involves a rotational component to the movement. In this technique the instrument is rotated clockwise or anticlockwise by a quarter of a turn and then removed. A drawback can be that the flutes can get locked into the dentine and then the instrument fractures as the operator pulls to remove it. However, there is less debris build up in front of the instrument and debris is removed as it is pulled from the canal. A variation of this technique is referred to as watch winding. This involves rotating the file anticlockwise and then clockwise in a 30-60 degree arc with light pressure directed towards the apex of the tooth, followed by pulling the file out of the canal. The file should not get locked into the canal, but should negotiate it, and it is especially useful in narrow canals where the file is pre-curved prior to insertion to mimic the shape of the canal.

3.11.3 Balanced Force

A further technique is called the balanced force technique. It was developed by Roane (Roane *et al* 1985) and involves a rotation clockwise of up to a quarter turn to engage the dentine as the flutes lock in. The operator then maintains apical pressure and rotates anti-clockwise a half turn to fracture the engaged dentine, and the file is rotated clockwise on removal. It was suggested that this technique would allow preparation of more curved canals with larger instruments without precurving, and help minimise canal transportation and ledging. The technique uses a triangular cross section file (Flex-R file) to increase flexibility with a modified tip (Powell *et al* 1986) that prevents aggressive engagement of dentine, and so allows the file to more easily follow the path of the canal. A reduced amount of debris pushed out of the canal beyond the apex and a clean apical region have been demonstrated after using this technique (Kyomen *et al* 1994), but apical transportation can result, and it is recommended to precurve the tip of the instrument in cases of more severe curvature.

Hand files can be manufactured out of stainless steel or nickel titanium. Nickel titanium hand files have been introduced (*e.g.* Niti Flex) due to their flexibility, and have been shown to reduce the incidence of ledges and procedural errors (Bishop and Dummer 1997). However, they do have a different feel to stainless steel files and have been shown to be less efficient at planing the canal walls (Schäfer 1997).

3.11.4 Rotational

The next preparation method is rotational. More recently a number of hand instruments have been designed that use a rotational action (ProTaper for hand use). These are specifically designed files that actively cut as they are rotated. This method of preparation is not recommended for other files as the chance of instrument fracture is high as it locks into the dentine. This method of file movement is, therefore, solely used for preparation of the canal rather than negotiation.

3.11.5 Patency

When a root canal is instrumented, dentine chips and pulp remnants can become packed ahead of the files, causing a blockage, and making cleaning and shaping very difficult. Attempts to break up this blockage can result in the apex becoming damaged by over-instrumentation, or becoming transported or ledged. Such problems are magnified in curved small canals, where the outer curve of the apical region is the most likely area for damage to occur. To minimise this it has been suggested to use a small 02 taper hand file (size 08 or 10) 0.5mm longer than the length of the root canal (Buchanan 1989) (Goldberg and Massone 2002) (Cailleteau and Mullaney 1997). This file is used in a push-pull motion with no rotation and serves to prevent blockage by keeping the foramen open. The advantages are the minimising of blockages, the carrying of irrigant into the deepest parts of the root, and preventing procedural errors. The disadvantages are potentially increasing the size of the foramen, carrying irritant debris into apical tissues which can contribute to post operative pain (Siqueira Jr. 2003), changing the shape of the foramen, especially in curved canals, and causing trauma to the apical tissues.

The use of a small patency file should not cause these problems, and should not increase symptoms for the patient after treatment is completed. However, it does rely on a careful technique and an understanding of apical anatomy.

3.12 Preparation Methods: Automated Preparation

3.12.1 Ultrasonic Instruments

'Ultrasonics' use ultrasonic energy in the 20-30 kHz range with conventional k type instruments to create vibration in a sine wave fashion. Ultrasonics work by acoustic microstreaming, where intense eddys are created in the fluid around the instrument, and cavitation, although there is some controversy as to whether this occurs within the confines of the root canal. Acoustic microstreaming is of great benefit in irrigation as it enables the irrigant to be distributed throughout the root canal system where instrumentation is not possible. Irrigation with ultrasonics has been proven to remove more organic tissue, planktonic bacteria and dentine debris from the root canal than when it is not used (Van Der Sluis *et al* 2007). Ultrasonics are not used in canal preparation as they can cause canal transportation (Zmener and Banegas 1996).

3.12.2 Rotary Endodontics

The first mention of rotary preparation was by Oltramare (Hülsmann *et al* 2005). He described the use of needles that were attached to a handpiece and rotated when full working length had been reached in order to amputate the pulp.

The first 360 degree rotational handpiece was used in 1889 (Hülsmann *et al* 2005) and used specifically designed needles at a speed of 100 revolutions per minute (rpm) to minimise fracture. Later handpieces were developed that had both rotational and vertical movement of the stainless steel instruments. The latest rotary systems use nickel titanium instruments and use either 360 degree rotation or a combination of forwards and reverse (reciprocating) to prepare the canals. The first modern handpieces using continual rotation were speed reducing that limited the speed of rotation of the file to help prevent instrument fracture and damage to the root canal. However, the high incidence of fracture gave rise to specially designed electric motors that had torque settings built in. The first motors used high torque to prevent the rotational speed of the file being reduced as load and resistance increased. Again, fractures were frequent and so variable torque motors were developed that allowed individual settings for load to be imported that were specific for each file used. The motors monitor resistance on the file during use, and then often auto reverse if the torque tolerance that is set is exceeded, and so minimise the risk of fracture. The torque settings for the various file systems differ considerably due to the file design. This is especially relevant for those with a variable taper. The thinner parts of these files have less tolerance to greater levels of torque and fracture more easily than the thicker more robust sections. This means that torque settings are difficult to set for such files, and rely upon good establishment of a glide path by the operator, so that the thinner apical part of the instrument is free and not under the same load as the thicker coronal parts of the file. Speed settings are also programmable for each file, depending on the manufacturers' recommendations.

Rotary file manipulation can be broken down into those which use continuous rotation and those that do not.

3.12.2.1 Non Continuous / Reciprocating Rotation

The Giromatic handpiece rotated 90 degrees clockwise and then reversed at 3000rpm. It used reamers, Hedstrom type files and broaches that were capable of preparing straight canals, but caused damage to curved canals as the files cut on their outstroke and tended to transport the apex, (Spyropoulos *et al* 1987) and therefore cause ledges, thus increasing the likelihood of perforations (Abou-Rass and Jastrab 1982).

The M4 handpiece worked in a similar way, but had a 60 degree rotation and used safety Hedstrom files at 1500rpm to help negotiate the canal. It has been associated with canal transportation, and is of limited use in canal preparation due to its inefficiency, but can be of benefit in negotiation of narrow canals using small K type files.

The 'Canal Finder' handpiece uses an up and down action with a 90 degree anticlockwise turn automatically if the file binds in the canal to help reduce fracture.

3.12.2.2 Continuous Rotation

Both stainless steel and nickel titanium files are used in a continually rotating manner. One of the earliest specifically designed rotating instruments were Gates Glidden burs. These stainless steel instruments have a bud-shaped cutting head with a safe non-cutting tip which corresponds to ISO sizes 50, 70, 90, 110, 130 and 150 and are numbered one to six (Saunders and Saunders 2003). They are used in the coronal one-third of the root to improve access and so facilitate canal negotiation.

A file of similar design was developed to prepare the entire root canal made out of nickel titanium called ‘Light speed’. This system uses a considerable number of instruments that are stepped back from the apex with sequentially larger instruments.

The rest of the rotary instruments use their taper to prepare the root canal. The taper of these instruments is either fixed or variable. Fixed taper instruments increase in diameter by a fixed amount with distance from their tip and range from an ‘02’ to a ‘12’ taper. Variable tapered instruments have varying shapes and dimensions with different files for preparation of the canal and finishing the apical one third.

The design of rotary files also varies considerably. Most are milled out of a blank of nickel titanium metal to a precise shape, for example ProTaper, although this is not exclusively the case, for example the ‘twisted’ file (SybronEndo). In the same way as hand files, the angle of rake on the instruments varies, which gives differing characteristics and efficiency in dentine removal. Due to the design of the cutting flutes, the files can be very efficient and tend to enable faster preparation with less operator fatigue and a reduced tendency to transport the canal from its original anatomy and produce procedural errors (Bergmans 2003). The first instruments had a radial landed design. An example of a file with this design is Profile, as shown in Figure 13, overleaf.

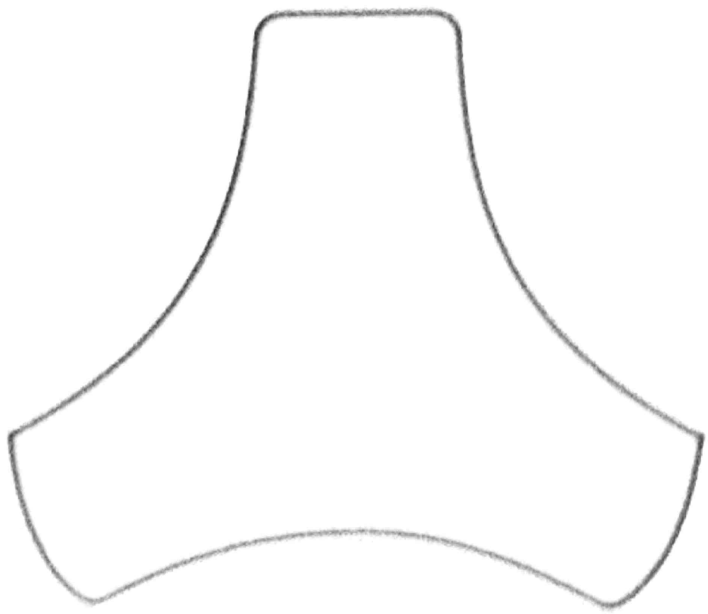

Figure 13: Radial landed design of Profile

The radial land allows removal of cut dentine via a U-shaped recess between the three cutting blades. The blades are neutral in their rake angle and so plane rather than actively cut the dentine. These files have been shown to be safe to use and maintain the curvature of the canal well (Rodig *et al* 2007) (Versümer *et al* 2002). However, they are slower in their speed of preparation, have a reduced tendency to remove cut dentine compared with other designs and use a greater number of files to prepare the required shape.

An example of a very efficient file with a variable taper is ProTaper. These instruments have sharp flutes with deep recesses between the blades for efficient debris removal and a faster preparation.

3.13 Preparation Methods: Conclusions

Rotary preparation of root canals brings benefits of speed of preparation and allowing a predictable shape to be created to accept a filling. Their use should be limited to preparation rather than negotiation, which is the role of hand files. The speed of preparation should not be used as the argument for their promotion, as the chemical aspects of debridement require a considerable amount of time to be effective. The true advantages are the efficiency of their dentine removal, and the predictability of the shape created with fewer procedural errors, which allows adequate chemical debridement and access of irrigating solutions to accessory canal anatomy.

3.14 Procedural Errors

To successfully clean and shape a root canal excellent access is needed to the root to minimise errors in preparation. Teeth are stimulated throughout life to lay down dentine as a protective mechanism which impedes access to the canals. The canals, when located, can have considerable curvature which may make negotiation to the apex difficult.

Schilder described the ideal preparation as being one with a continuous taper wider at the coronal portion and narrowing to the apex. There are a number of errors that can occur when shaping root canals. These include blockages, zips, ledges, perforations and fractured instruments.

As a root canal is instrumented, the canal is enlarged and shavings or chips of dentine are removed from the canal wall. This facilitates negotiation of the canal, but can result in blockage as the shavings may become packed ahead of the instrument in narrow canals (Siqueira Jr. 2005). This problem is often created by the first files used to negotiate the canal. If too large a file, or too much force is used, then the canal becomes blocked. This can prevent the passage of small files to the end of the canal.

In root canal preparation the coronal part of the root is located and prepared first. This removes the bulk of bacteria from the area where the concentration is at its highest (Shovelton 1964). It also serves to remove the bulk of pulp tissue, which if not removed at this stage by a mixture of mechanical removal and dissolution in the irrigating solutions can become packed into the root canal and block the passage of files. This pulp tissue if vital also bleeds and impedes vision.

It is not recommended to negotiate to the end of the canal initially, rather to clean the coronal portion before the apical third is explored, as bacteria can be introduced from the coronal section to the apical where they are more difficult to remove. It also helps prevent blockages by the pulp remnants as they are removed coronally and creates space for irrigant to be present when the apical region is explored.

Any instrument may fracture or break in a root canal (Cheung 2007). A broken or fractured instrument blocks the root canal and prevents further negotiation, inhibiting disinfection.

Root canals are rarely straight. Greater curvatures increase instrument stress and therefore the chance of procedural errors (Lam *et al* 1999). A ledge is created when the file attempts to continue in a straight line rather than the curved path of the canal. As the root curves and the canal narrows, it becomes more difficult to negotiate. Larger diameter instruments naturally become less flexible as their size increases. This makes it more difficult for them to negotiate curves or bends. In response to these challenges, the design of files and the materials from which they are manufactured has changed to provide different characteristics such as improved flexibility. However, files preferentially cut on the outside of a curve in the apical region and on the inside of the curve more coronally as they attempt to straighten and take the most direct path to the foramen (Tang and Stock 1989), especially when in the tight confines of a root canal. If the file is worked in the same position for sufficient time a ledge may be created in the dentine wall on the outside of the curve. This can be difficult or sometimes impossible to smooth out, and can make further instrumentation past it difficult.

If the ledge is too large to renegotiate, or if the operator does not realise that it is not the original path, then the damage to the root canal wall can continue until the side of the root is breached and a communication with the periodontium established which is known as a perforation. This may result in the original anatomy beyond the perforation being unprepared and not cleaned, resulting in bacteria remaining in the canal. This increases the likelihood of the root canal treatment failing and also compromises the seal of the canal as an additional, frequently irregular exit has been created. If large instruments are used through the foramen past the constriction, then as the canal is instrumented the apical foramen is transported away from its original position and made wider creating a preparation defect frequently referred to as a zip.

3.15 Step Back and Crown Down

The traditional way of preparing a root canal involved measuring the length of the canal from a radiograph and shaping it from the apical constriction to the orifice. This is called step back (Hankins and El Deeb 1966). Firstly the canal was located and the access established. The coronal part was enlarged to enable an irrigating needle to deliver solutions into the canal, and also to facilitate negotiation of the root canal to the constriction, and so establish the canal length. Stainless steel hand files (02 taper) were used to sequentially enlarge the canal, with each successively larger instrument being used incrementally shorter (stepping back) than the full length to create a taper. The apical and coronal preparations were thus blended together to create the overall shape.

Problems can occur with this technique if it is used in curved canals where larger files are used to the full working length. The inherent stiffness of the larger sized stainless steel files means that they will not remain central within the canal and so preferentially cut the outside of any curve apically and the inner wall more coronally, producing procedural errors such as zips and elbows, and resulting in narrow preparations that restrict irrigant penetration. The balanced force (Roane) method of manipulating files was developed in order to reduce canal transportation and enable larger file sizes to be used apically in curved canals with the files remaining central within the root.

Crown down preparation involves preparing the coronal part first followed by the apical (Morgan and Montgomery 1984). This method ensures bacteria and pulp tissue is removed from the most contaminated areas (Shovelton 1964), rather than pushed apically. As the coronal part is prepared, interferences are removed which can prevent apical progression (Blum *et al* 1999), and a reservoir of irrigant exists which allows better debridement and access into accessory anatomy. One of the main advantages is that as the coronal part has been prepared before the length of the canal has been measured, the length is unlikely to change as much as in step back in curved canals. Crown down also allows a better tactile sensation of the apical region (Stabholz *et al* 1995) and reduces the chances that files will bind and separate in this region.

3.16 Irrigation

The chemical aspect of debridement of the root canal is completed using a number of substances that are concerned with killing bacteria and dissolving the organic tissue of the pulp (Haapasolo 2010).

3.16.1 Sodium Hypochlorite (NaOCl)

Sodium hypochlorite is the most widely used irrigating solution (Mohammadi 2008). It is an effective antimicrobial (Spratt *et al* 2001) which dissolves pulp remnants. It is commonly used in concentrations from 0.5 to 6% either at room temperature or heated which serves to increase the available concentration of HOCl which is responsible for antibacterial activity. The concentration is important as it is a measure of the active ions available in the solution (Haapasolo 2010). A higher concentration has more ions, but has been proven not to be proportionally more effective than lower concentrations. However, it is relevant that the concentration does need to be above 2% to have dissolving characteristics necessary for removal of vital and necrotic tissue.

Hypochlorite has strong antimicrobial activity at even weaker concentrations (Bystrom and Sundqvist 1983) and kills bacteria very rapidly. It is active against most bacteria found in the root canal.

3.16.2 Ethylenediaminetetraacetic Acid (EDTA)

EDTA is not an effective antimicrobial. It has an effect on inorganic tissue and helps to remove the debris that becomes compacted into the dentinal tubules when the root canal is instrumented. This debris, which includes soft tissue and dentine components is referred to as the smear layer and prevents thorough irrigation of the root canal system (Violich and Chandler 2010). EDTA has been shown to increase the antibacterial effectiveness of sodium hypochlorite when used in the same irrigating regime (Bystrom and Sundqvist 1985).

3.16.3 Chlorhexidine (CHX)

Chlorhexidine has a wide range of antimicrobial properties (Mohammadi and Abbott 2009). It also has the advantage that it is not toxic and will not bleach patient's clothing unlike hypochlorite. It needs to be used in a concentration above 2% to be effective, but doubt has been expressed as to whether the solution is less effective when organic dentine is present, as it is in root canals. It also lacks the tissue dissolving ability of hypochlorite (Naenni *et al* 2004).

3.16.4 Iodine

Iodine compounds are capable of killing bacteria, are non toxic, but some patients can demonstrate allergy to them. Iodine is used as iodine potassium iodide (IKI) and has proven to have activity against the resistant *enterococcus faecalis* bacteria found in failing root canals (Peciuliene *et al* 2001). It is less effective as an antimicrobial than hypochlorite and chlorhexidine and again is less effective in the presence of organic dentine.

3.16.5 Citric Acid

Citric acid is also used in removal of the smear layer and is again not an effective antimicrobial on its own, and has been shown to decrease the efficacy of sodium hypochlorite (Zehnder *et al* 2005).

3.16.6 Saline and Local Anaesthetics

Saline and local anaesthetics are not effective antimicrobials (Sena *et al* 2006) and have no tissue dissolving capabilities. They cannot remove the smear layer and are not used in root canal therapy as irrigants.

3.17 Lubricants

Lubricants are used to facilitate instrumenting the root canal. They make the negotiation of canals easier as they help movement of the file within the root. They are used in the early stages of canal negotiation and shaping. Lubricants, for example 'Glyde', contain glycerine to lubricate and often EDTA to help dissolve the organic component of the pulp.

3.18 Conclusions

The ideal irrigating solution should be an effective antimicrobial, dissolve pulp remnants, be non toxic and remove the smear layer. Unfortunately, none exist that can do all of these things. This means that when treating the root canal system a number of chemicals are required and are used as part of an irrigating regime. Knowledge of the cause of the infection that the operator is treating, which bacteria are likely to be present, and what the properties of the available chemical solutions are, is a prerequisite to enable optimal chemical debridement and therefore promote healing.

3.19 Obturation

Obturation is the filling of the root canal after cleaning and shaping have been completed. Before obturation the canal must be dry and have no symptoms. Obturation serves to mummify any bacteria that have not been killed during cleaning and shaping within the root canal, and prevent them from thriving. It prevents bacteria and their toxins leaking into the periodontal tissues causing inflammation and infection, and seals the canal from bacterial ingress (Lumley *et al* 2006). It is done using inert materials to provide a seal accompanied by a sealer to fill any accessory anatomy not filled by the obturation material.

Root canal filling materials can be divided into solid or semi-sold types, pastes and sealers, and cements. The most commonly used filling material is a semi-solid rubber called ‘gutta percha’, which is available in shapes and sizes to match the files used to prepare the root canals.

Previous root filling materials have included silver points which produced corrosion and allowed bacteria to leak into the canal, and pastes which were spun into the canal with a rotating spiral filler (Whitworth 2005), but were cytotoxic and could not be easily controlled (Hauman and Love 2003).

New technologies are constantly being researched regarding obturation to find a material that is biologically inert, easy to use, bonds and seals to the canal wall, easily seen on an x-ray, impervious to moisture, kills microbes and is non-toxic. At present no material meets all these criteria. Gutta percha is the current material that meets many of these. It is introduced as a tapered cone or via plastic carriers, often with the same taper and dimensions as the files used in preparation and can be heated or introduced under pressure to allow it and the sealer to flow into and fill accessory anatomy.

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4 Use of Nickel Titanium (NITI) Root Canal Instruments

4.1 Introduction

The number of rotary nickel titanium file systems on the market today indicates the growth in this area of endodontics. There are numerous systems with differing designs in terms of their taper, (fixed or variable), or flute design, (radial landed or bladed). All claim advantages in terms of speed (Thompson and Dummer 2000) (Guelzow *et al* 2005), efficiency (Jardine and Gulabivala 2000) and ease of use (Moore *et al* 2009). All root canal files are now designated as single use instruments (Department of Health 2007) as they must be discarded after treatment is completed on a patient. This has encouraged manufacturers to investigate how they can produce file systems that use fewer instruments to achieve the same end product in terms of shape and therefore save on consumable costs.

4.2 Root Canal Shaping

The role of root canal shaping is the removal of bacteria and infected dentine from within the root canal system and the creation of a smooth progressively tapered preparation that will facilitate debridement and subsequent filling to prevent re-infection.

The ideal preparation should possess a progressive taper with the original anatomy of the canal maintained; the canal should get narrower as it goes from coronal to apical with the end of the preparation in the original position of the apical foramen and not over enlarged (Schilder 1974).

Preparing root canals brings considerable challenges (Blackler 1998) as they can be severely curved and difficult to access. The greater the curvature, the more the likelihood of procedural errors (Greene and Krell 1990) and the creation of zips, elbows and perforations (Nagy *et al* 1997), as described in Section 3.14.

4.3 Hand Nickel Titanium

Hand nickel titanium instruments are split into those for canal negotiation and those for preparation. Those for negotiation are manufactured as an alternative to stainless steel files and have an 02 taper and conform to ISO guidelines, for example *Ultra Flex* files. For negotiation, nickel titanium has the advantage of flexibility and the ability to remain central within the canal (Short *et al* 1997) (Carvalho *et al* 1999), and can help reduce canal transportation (Chan and Cheung 1996) (Lam *et al* 1999). It can also be pre curved (Walia *et al* 1988), as is done with stainless steel hand files (Lambrianidis 2006), which can aid the operator to find and instrument accessory anatomy, or help negotiate canals if any procedural errors have occurred during negotiation or preparation. However, it does give a different feel to stainless steel files and provides less feedback to the operator. These factors can limit their use until negotiation has been completed using stainless steel files.

Files for preparation are available that possess either fixed or variable tapers, and are used in a number of ways. Hand GT (greater taper) files have a fixed taper of 06, 08, 10 or 12. They have a tip size of 0.02mm and a maximum diameter of 1mm to limit over-preparation of the coronal portion. They are used in a variation of the balanced force method (Roane *et al* 1985) (as their flutes are counter-clockwise) with the initial rotation counter-clockwise to engage the dentine, then clockwise on removal rather than the opposite for balanced force (Buchanan 1996). These files have been shown to give good deep shaping, although it has been suggested that 02 taper hand files are still needed to gauge and finish the apical part (Lumley 2000). An example of a hand nickel titanium file that has variable taper is *ProTaper* (which will be described later). It is available as hand or rotary variants.

4.4 Rotary Nickel Titanium

Traditional hand instruments have a fixed taper whereby the diameter increases from the tip along the instrument by a fixed factor as distance increases from the tip.

Rotary nickel titanium files have fixed or variable tapers where the taper is smaller at the tip, and increases with distance from the tip.

Files with larger tapers are normally used in a larger to smaller crown down fashion, rather than the traditional step back method. With crown down, less flexible greater diameter files are used first. A drawback with this method can be a risk of taper lock (Spångberg and Haapasalo 2002) with the flutes engaging dentine along their entire length, resulting in fracture. The advantage to the technique is the removal of the highest concentration of bacteria first before preparing the apical region, and enabling good access for both files and chemicals to disinfect the system.

Rotary nickel titanium files are used in an electric torque sensing motor that is normally programmable to allow settings for different file systems to be imported. The motor stops rotation if the load on the file exceeds a specified value and will often auto reverse, and so help minimise the risk of file fracture.

An example of a rotary nickel titanium file with variable taper is ProTaper.

4.4.1 ProTaper

Teeth vary significantly in their anatomy. A file system has to adapt to differing anatomies along the entire length of the root canal. ProTaper uses a 'crown down' way of preparation where the bulk of dentine is removed initially from the top and middle parts of the root before progressing to the end. ProTaper instruments have a triangular cross section. This design minimises contact between the file and the canal and so decreases the load when it is cutting, and so increases the efficiency. The angle and pitch of the cutting blade continuously changes along the length of the cutting flutes (Ruddle 2005) to ensure effective dentine removal and stops the file being pulled and screwed into the canal.

ProTaper instruments are grouped into Shaping and Finishing files. The Shaping files are used first. The files have a small tip diameter with a narrow taper at the tip which then increases as distance increases from the tip. This results in the tip of the file when in use not being active, but acting to guide the body of the instrument along the canal path. This minimises the chance of taper lock, and means that only the strongest and most efficient part of the instrument is active, therefore reducing the chance of breakage. The Shaping files are designated S1 and S2 and are used in the upper and middle parts of the canal. The Finishing files have a fixed taper for the last 3mm of the file which shapes the end of the root canal. The taper of the file reduces from 3mm to the coronal end which means most of the cutting is done in the apical third. The Finishing files are designated F1 and F2, F3, F4, F5.

The diagram below shows the differences between Shaping and Finishing file shapes.

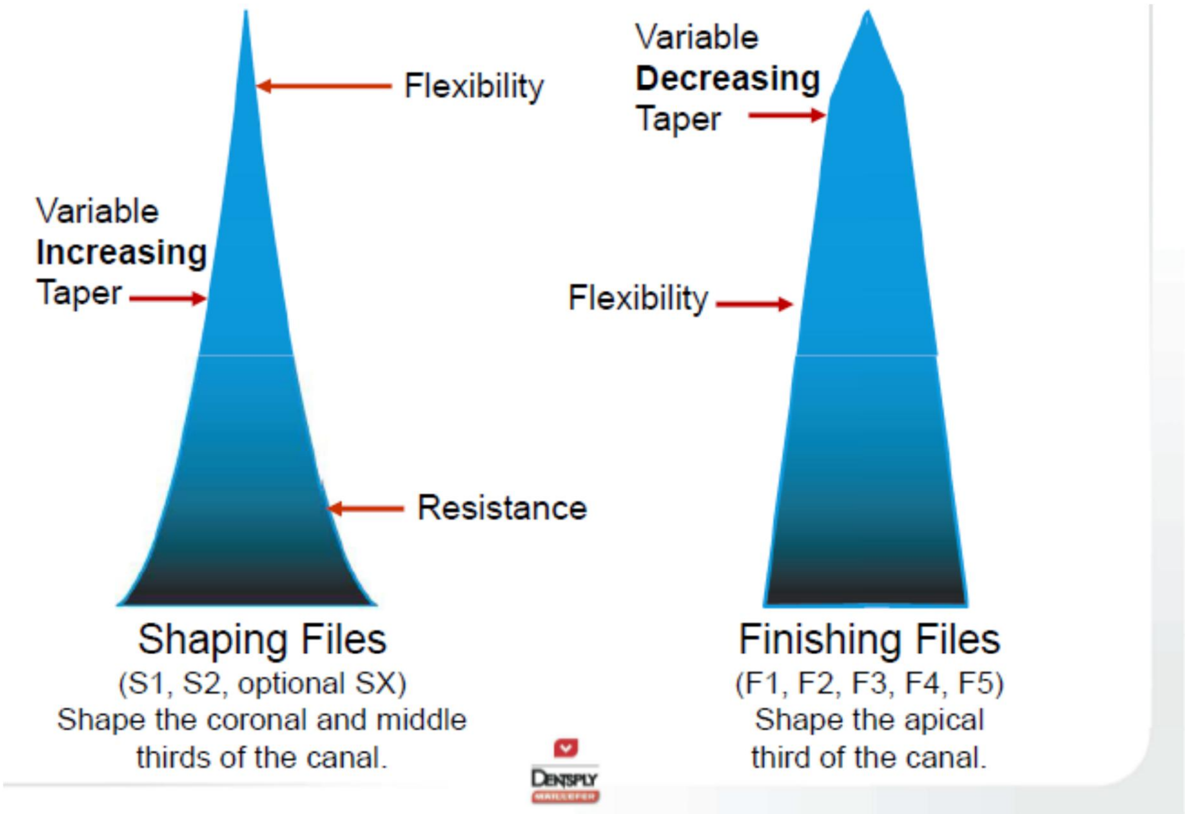

Figure 14: The differences between Shaping and Finishing file shapes (images courtesy of Dentsply Maillefer)

ProTaper has a triangular cross section to decrease the contact with the root canal wall and so minimise the screwing in effect. The shape ensures a high degree of flexibility, but also strength and therefore helps resistance to fracture. The Shaping files have a different cross section to the Finishing files, with the Finishing files having a concave cross section to increase their flexibility.

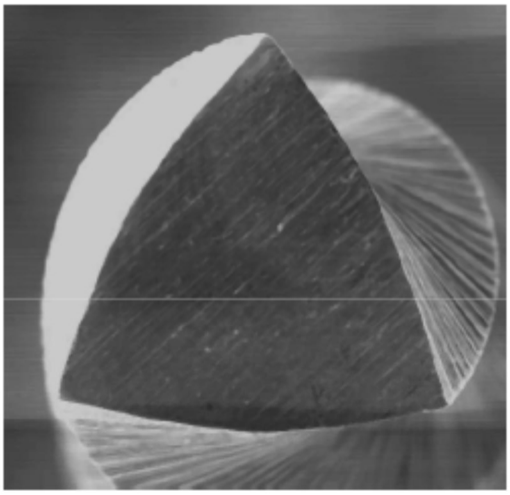

Figure 15: Triangular cross section of Shaping files (images courtesy of Dentsply Maillefer)

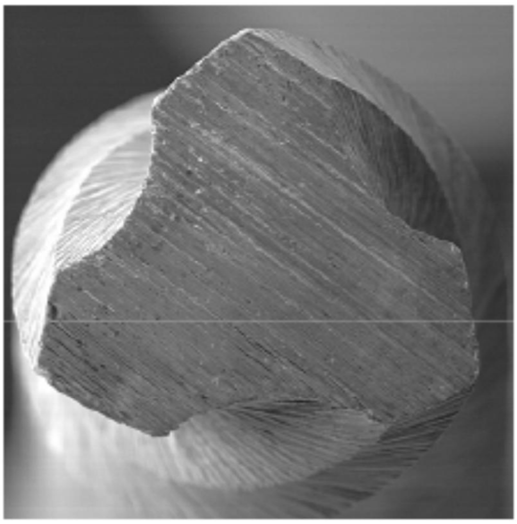

Figure 16: Cross section of Finishing files (images courtesy of Dentsply Maillefer)

ProTaper have an optimal helical angle with variable pitch on the cutting flutes, designed to maximise efficiency and again prevent the file screwing into the canal.

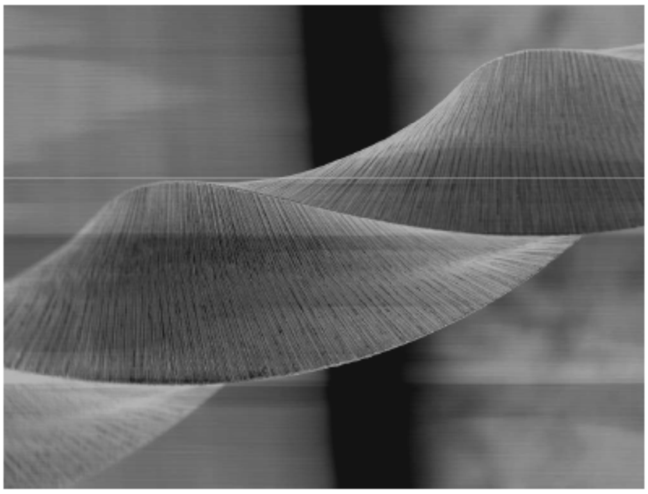

Figure 17: *The design of the flutes (images courtesy of Dentsply Maillefer)*

The tip design is a modified non-cutting tip which acts as a guide in the root canal but does not cut.

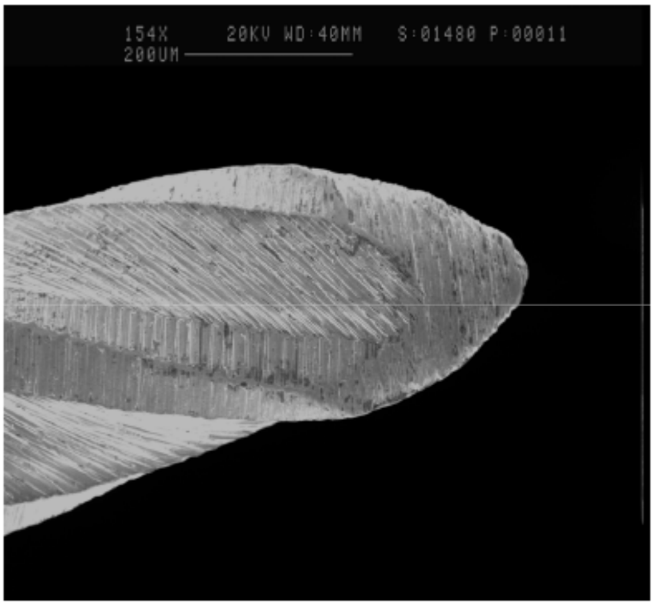

Figure 18: The design of the tip (images courtesy of Dentsply Maillefer)

ProTaper files have been shown to produce well centered preparations, with minimal transportation and loss of working length (Iqbal *et al* 2004). However, they are associated with straightening of the canal, especially where the apical curvature is more severe or where the larger Finishing files are used due to their reduced flexibility (Calberson *et al* 2004) (Plotino 2007).

4.4.2 Reciprocating Action

Numerous handpieces have been designed that use a combination of clockwise and anti-clockwise rotation of files, for example the Giromatic, which used reamers, Hedstom files and broaches to prepare canals. More recently it has been suggested that a ProTaper file could be used in a handpiece with a reciprocating action where the clockwise and anti-clockwise and backwards rotation is timed, rather than dictated by the degrees of rotation. The reciprocating technique uses the F2 Finishing file from the ProTaper sequence to both shape and finish the preparation after negotiation with hand files. The advantage of the method is simplification and the time taken to prepare. There is also a great cost saving. Files in root canal treatment are only used on one patient, and so the cost of equipment is high. Using only one file obviously has a great advantage in terms of cost, and this is a great advantage for this technique.

4.5 Conclusions

Hand nickel titanium files have been shown to have some benefits over stainless steel (Schäfer *et al* 1995). They are more commonly used for preparation rather than negotiation, and can have increased tapers that allow better irrigant access to the apical region and efficiently remove debris from the root canal system. Their greatest benefit is in more curved root canals where instrumentation with stainless steel files can result in narrow preparations with procedural errors due to their inflexible nature. Hand nickel titanium files have an advantage over rotary when the access for a handpiece is difficult and where the apical curvature is more severe. Rotary nickel titanium files have great advantages in terms of their cutting efficiency and debris removal. They prepare canals much more quickly than hand files with a reduced risk of canal transportation and better maintenance of the original canal shape than stainless steel (Guelzow *et al* 2005) (Peru *et al* 2006). However, they are instruments for canal enlargement and shaping, and an understanding of the anatomy of the canal and knowledge of the limitations of each file system is vital in order to minimise errors and ensure predictable and safe preparation of root canals.

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5 Evaluation of Root Canal Instrumentation

5.1 Introduction

The goal of endodontic treatment is the removal of bacterial infection from within the root canal system or the prevention of such an infection becoming established. To do this the root canal must first be accessed and then cleaned and shaped. Cleaning and shaping is performed by a combination of mechanical removal of the necrotic (infected) and vital (non infected) root canal tissue as well as some dentine from the root canal wall (Hülsmann *et al* 2005), and chemical disinfection by removal of bacteria and their products from within the root canal space.

Root canals are rarely straight and have a varying degree of curvature along their length. This brings challenges in preparation as the instruments used can become stressed as the degree of curvature increases (Zelada *et al* 2002). It can become difficult to access these areas successfully along the entire length of the canal. A number of difficulties may be encountered which can create errors in preparation such as zips elbows, ledges and perforations, which were described in Section 3.14.

Root canals contain accessory anatomy with communication between the pulp and the periodontium and communication between different areas of the pulp in the form of isthmuses (Vertucci 2005). It is impossible to instrument all of these areas (Weiger *et al* 2002), so it is very important to maximise exposure of chemicals to disinfect them by creating access for both files and chemicals by instrumenting the entire length of the root canal.

5.2 Assessment of Mechanical Shape

Mechanical shaping may be assessed by how well the ideal preparation shape has been accomplished. The degree of taper, amount of tooth tissue removed (Yoshimine *et al* 2005), transportation of the apex (Javaheri and Javaheri 2007) (Goldberg and Massone 2002) (Gergi *et al* 2010), centering ability (Gergi *et al* 2010) (Short *et al* 1997) (Aguiar 2009), blockage of the root canal, creation of elbows, zips and perforations and breakage of instruments (Zelada *et al* 2002) (Cheung 2007), may all be evaluated. The main methods of doing this are using either simulated root canals or extracted human teeth.

5.2.1 Simulated Root Canals

Simulated root canals are made out of resin and have a central canal with a fixed curvature and diameter. In some instances, authors have constructed their own canals using silver points which are bent using formers to an angle, and then encased within a self curing acrylic resin (Weine 1975) (Thompson and Dummer 1997) (Bryant *et al* 1998) (Dummer *et al* 1991), thus allowing the authors to prescribe the degree of curvature of the canal. When used in studies to compare different file systems, the simulated canal can help to standardise the canal dimensions to be prepared and the amount of stress placed on the file. The use of a resin also allows the hardness to be standardised, whereas in a tooth the hardness of dentine can vary dramatically. The simulated root canal has a hardness commonly in the 20-22kg/mm^2 region whereas dentine varies from 35-40kg/mm^2 (Hülsmann *et al* 2005). This means that the resin canal is less forgiving and more likely to reveal procedural errors. Simulated canals allow direct comparison of different methods or file systems as the canal dimensions are manufactured to be the same. The use of resin blocks has been criticised because the size of the resin chips produced when they are prepared means the blocks are more likely to get blocked than a root canal, but again replication between groups allows inter-group control in this area.

The resin block contains a canal of a specific length and curvature. Where the ability of an instrumentation system to prepare to a specific point is being assessed, the standardisation of length is of paramount important. Resin blocks enable visualisation of how much material has been removed and how accurately the length of the preparation has been maintained. One of the main reasons for their use is the ability to superimpose ‘before and after’ preparations, and use computer software to assess the change in shape. They may also be photographed to further assist in evaluation.

5.2.2 Human Teeth

It is more difficult to compare root canal preparations performed in human teeth due to them firstly not being transparent, and also due to the variability in their anatomy (Hess and Zurcher 1925). Favoured techniques are to use the same type or class of tooth roots. For example, upper incisors are commonly used for the assessment of cleaning and disinfection as the canals are often more straight, and the mesial roots of lower molars (with two separate canals) are often used to assess preparation techniques as they tend to have a degree of curvature that is gradual rather than severe (Jungmann *et al* 1975). The lack of transparency of root canals has been addressed in a number of ways using radiographs, clearing, the Bramante technique and micro computed tomography, all of which are considered below.

5.2.3 Radiographs

Radiographs provide an indication of root canal anatomy, however, there are difficulties comparing before and after preparations for analysis (Omer *et al* 2004). Radiography is also somewhat subjective, and only allows limited conclusions to be drawn as it is difficult to measure differences owing to the two dimensional nature of the image. One method of comparison is between a radiograph taken pre-operatively and one taken post operatively (Backman *et al* 1992). The limitations of this method include the two dimensional nature and relatively low resolution of the resultant image. The two dimensional image means that if the curvature is in the same direction as the radiograph is exposed, it will appear straight rather than curved (Hülsmann and Stryga 1993).

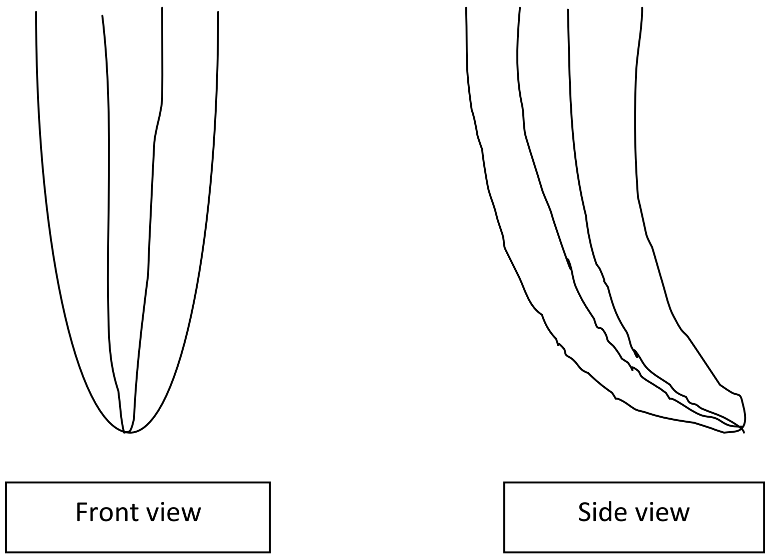

Figure 19: Front and side view of the same tooth

It is also very difficult to interpret the location of the major canal foramen on a radiograph. This makes comparison of the preparation in terms of movement and deflection of the main canal and foramen with respect to Schilder's principals very difficult.

5.2.4 Clearing and Silicone

Clearing is a way of rendering teeth transparent following either injecting India Ink to demonstrate anatomy, or silicone impression material to demonstrate canal shape.

The traditional technique involves removing the pulp remnants after accessing. An ink is injected, sometimes with negative pressure vacuum suction, and then the tooth is de-calcified, dehydrated and placed in methyl salicylate to render it transparent. This allows good visualisation of the root canal and it has been recommended as a useful teaching tool (Omer *et al* 2004). The technique was later modified by Weng *et al* (2009) to enable better representation of the apical region by using hyperbaric oxygen and positive pressure to distribute the ink better though the root canal system.

The technique enables excellent three dimensional (3D) visualisation of the canal space and shows the extent of the connections and accessory anatomy that exists.

However, it is not possible to compare before and after preparations as the tooth is changed in terms of its structure in the clearing processes and so cannot be prepared afterwards.

Silicone has been injected into prepared root canals (Haga 1968) (Davis *et al* 1972) and then the tooth around it either rendered transparent or dissolved (Goldman *et al* 1989). This allows examination of the root canal space, but again cannot be used to examine pre and post treatment groups as the method can be very destructive, and is rarely used. It has also been criticized as difficult to perform reliably, and is limited to canals of a sufficient size (Chen and Messer 2002).

5.2.5 Sectioning

Bramante attempted to address the problem of analysis of pre and post root canal preparation in three dimensions, by creating a model that contained a tooth embedded in resin that was sectioned along its length at specific points (Bramante *et al* 1987). The sections were photographed, and the model reassembled and held in place by an external muffle while the root canals were prepared. After preparation, these sections could again be removed and the change in horizontal shape assessed. This method is often used to assess the centering ability of files (Kuhn *et al* 1997). A disadvantage is that before and after shapes in the long axis of the tooth are much more difficult to evaluate, and it is also difficult to study sections very close to one another due to the destructive nature of the root sectioning, with apparent ledges created due to gaps where the tooth has been sectioned and reassembled (Deplazes *et al* 2001).

Numerous authors have suggested variations to this model, including the endodontic cube (Kuttler *et al* 2001). Here a resin is used to reproduce entirely the shape of the tooth to be examined and more accurate and reproducible guides are created to allow better assembly later, and therefore allow more reliable comparisons.

5.2.6 Micro Computed Tomography (Micro CT) and Micro Computed Cone Beam CT (CBCT)

Micro CT and CBCT have been used to measure changes in the root canal (Peters *et al* 2001) (Garip and Günday 2001). They enable comparison in all dimensions and can be used to compare volume as well as dimension changes within the canal space. It utilises computer software to capture the pre and post preparation image which can then be compared. The techniques are very expensive and time consuming (Gambill *et al* 1996), which can be preventative when using a large sample size. However, it is possible to study great detail and with excellent accuracy (Rhodes *et al* 1999) (Nielsen *et al* 1995).

5.3 Conclusions

Many authors have used a variety of methods to compare root canal preparation. These have ranged from simulated canals used to compare shape changes and used for visualisation of the shape versus a set of goals or ideals, to the most recent micro CT experiments measuring volume changes using advanced computer software.

All the methods have advantages and disadvantages. Clearing and silicone techniques do not enable before and after comparison, micro CT is very expensive, and radiography only enables simple comparisons, but no more. The use of different techniques is targeted to the needs of the investigation performed and ultimately what the operator is trying to evaluate.

It was decided to use resin blocks in this study as this allows comparison of pre and post preparation shapes, allows standardisation of canal dimensions so that the effects of different techniques on the same canal shape can be studied, and would enable operators to see the canal as they completed the preparation.

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6 Materials and Methods

6.1 Introduction

The aim of root canal preparation is to produce a smooth, constantly tapered shape with the canal anatomy maintained and the apex in its original position without over enlarging the canal and weakening the root. The production of a tapered preparation maximises irrigation and debridement of the root canal, and subsequently allows placement of a root filling to seal and prevent future re-infection of the canal system. Root canals are not always straight and usually have a degree of curvature along their length. It is this curvature that poses many problems, especially at the apical portion where access is more difficult and the mechanical properties of the files result in difficulties in maintaining root canal curvature. To combat these problems files manufacturers have developed instruments made from different metals (for example nickel titanium) to improve their flexibility. This decreased stiffness also allows instruments with different and increased tapers to be manufactured which more efficiently prepare and remove debris whilst enlarging the root canal.

The way in which files are manipulated has also changed over the years. Originally files were used by hand in a push-pull, or clockwise and anticlockwise rotation, or in a combination of both. Presently, electric torque sensing motors exist that drive a handpiece into which files are inserted. The motors are programmable for different instruments and allow settings to be adjusted depending on the file system being used. Some of these motors are capable of either constant clockwise or a combination of clockwise and anticlockwise rotation.

Often several instruments are required to negotiate and prepare root canals due to their intricate and complex shape. Root canal instruments have been designated as single use (Department of Health 2007) and must be discarded after treatment of a patient. This means that there are considerable consumable costs involved in endodontics, and manufacturers are competing to produce file systems that can help achieve the aims of preparation with fewer instruments and so save on consumable costs.

The aim of this study was to evaluate the differences in preparing simulated root canals using two different preparation techniques using resin blocks which were covered with tape (*i.e.* the operator could not see the canal space) or uncovered (i.e. unrestricted vision). The former is more challenging as the operator cannot see the anatomy of the canal and it may be argued that this is more representative of the clinical situation where root canals are instrumented blindly as the tooth root is surrounded by alveolar bone.

In summary, therefore, this work had two objectives:

- To evaluate two root canal preparation techniques: rotary and reciprocating.
- To see if covering the block so that the operator was instrumenting the canal "blind" affected the quality of canal preparation compared to uncovered.

Canal shaping was evaluated against the requirements of root canal shape as described by Schilder (1974).

The method used to conduct the study is described below. A pilot study was also undertaken to test the method and also the technique for image recording and analysis.

6.2 Simulated Canals

A new model system was developed specifically for this project. Endodontic training blocks (manufactured by Quality Endodontic Distributors Ltd) were used to compare the techniques. The blocks had a canal length of 19mm with a curve of 45 degrees in the apical third. 150 blocks were used in total. They were individually etched with a number and then again marked with the same number in indelible ink so that it could clearly be seen and ensure unambiguous identification. The etching was done so that if the indelible ink number rubbed off, there would be an alternative way of recognising the block. The blocks were then injected with black India Ink (Daler-Rowney non clogging) to allow the canal to be clearly visible when photographed and allow the evaluators to see any areas that had not been prepared after shaping had been completed.

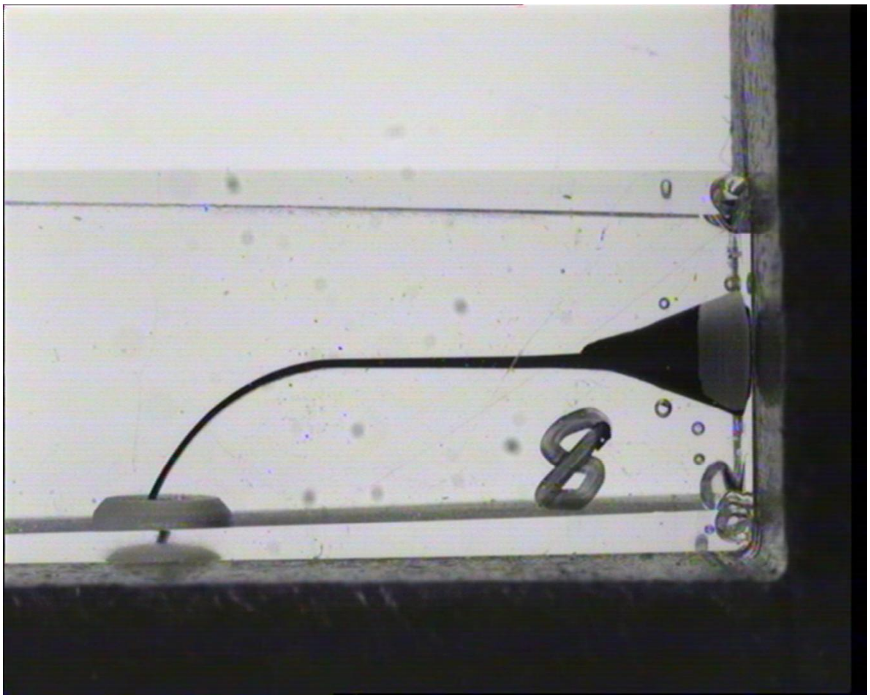

Figure 20: Simulated canal stained with ink

6.3 Image Capture

The blocks were all photographed before preparation. A fixed camera (black and white video camera manufactured by JVC) was used to enable exact replication of the image so that pre and post preparation images could be superimposed. The fixed camera also eliminated magnification and distortion of the image so that images could be compared for analysis of the results.

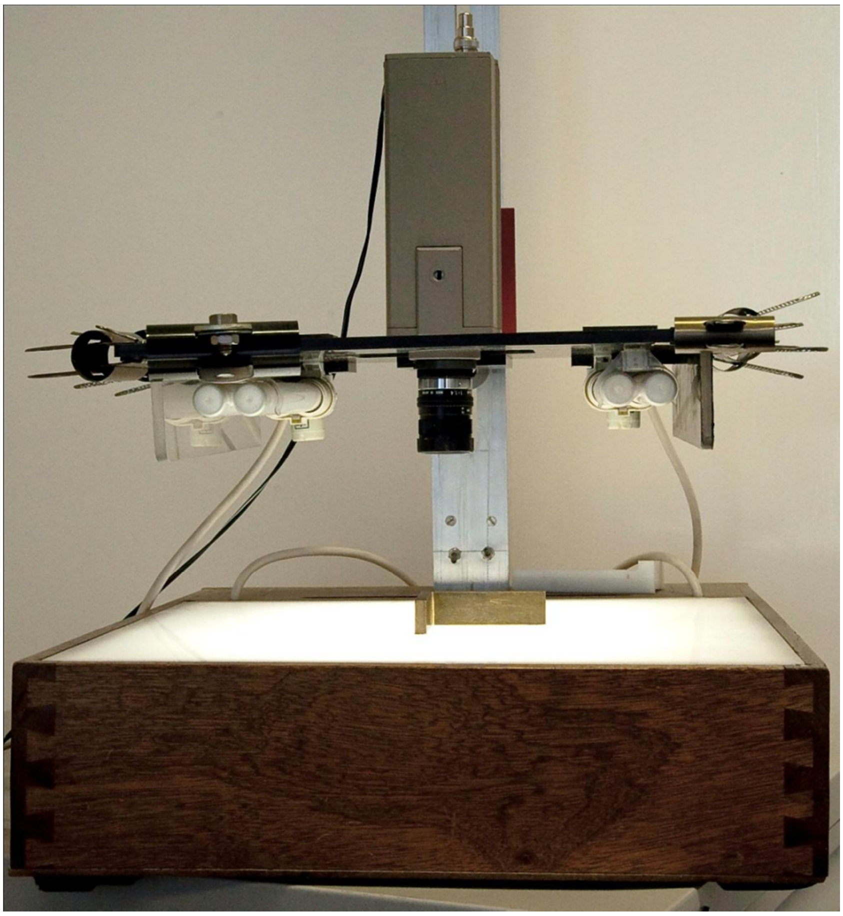

Figure 21: Platform and camera for image capture

The camera was mounted on a metal arm above a light box that had a piece of 'L' shaped metal permanently attached to its surface to place the blocks against. This prevented the blocks from moving, allowed each one to be in the same place when photographed, and permitted re-superimposition when the post preparation image was taken. A stage was arranged just above the camera lens that had two strip lights attached to enable good illumination. The camera was a black and white video camera connected to a computer (Dell Inspiron) to record and store the images.

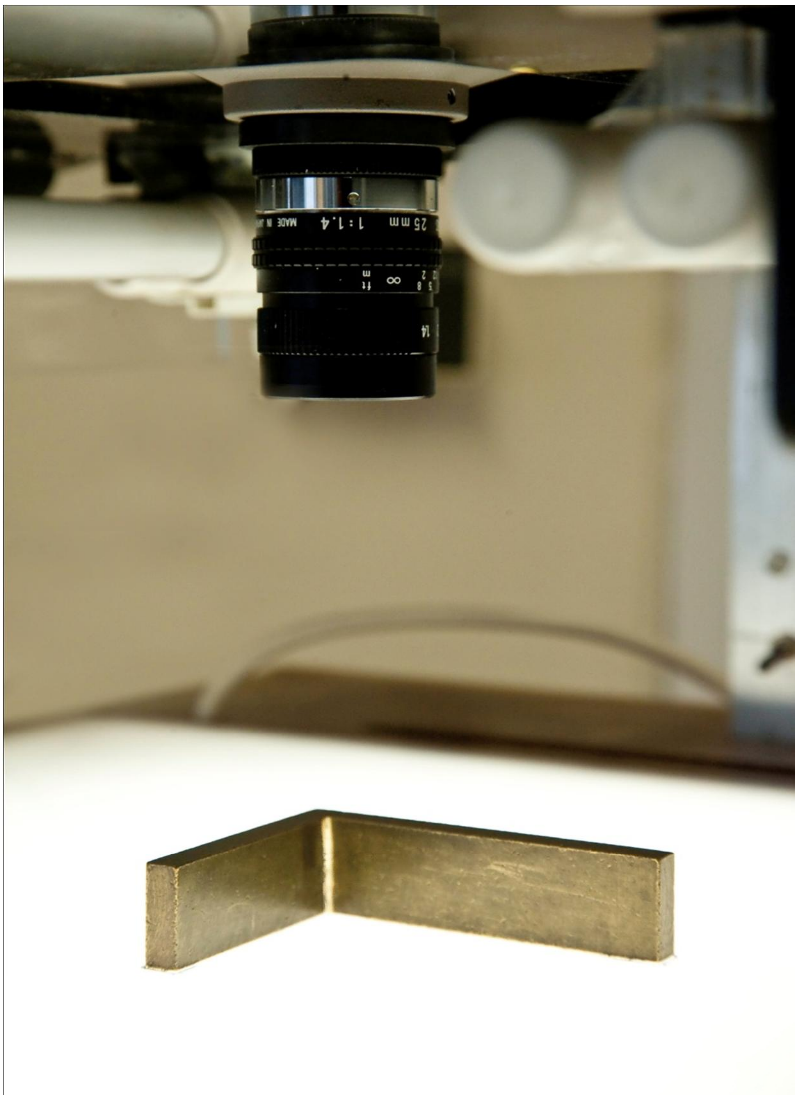

Figure 22: 'L' shaped metal to place blocks against

6.4 Instrumentation

Negotiation and creation of the glide path was done using stainless steel hand Flex O files (manufactured by Dentsply Maillefer). These files had an 02 taper with a tip size of 10, 15 and 20. These instruments are manufactured from a blank of stainless steel ground to a triangular section (although smallest sizes may be square) and then twisted to form the file (see Figure 9, page 55).

Preparation was done using ProTaper (manufactured by Dentsply Maillefer) rotary nickel titanium files. These instruments have a variable taper and are available in both rotary and hand variants. ProTaper files are manufactured from a blank of nickel titanium and ground to shape. The hand and rotary instruments are identical other than the hand files have a plastic handle and the rotary files have a machined end to fit into a handpiece. There are two types of ProTaper files designated 'Shaping' and 'Finishing' files. All instruments have a triangular cross section with the Shaping files having a triangular convex cross section to improve strength, and the Finishing files having a triangular concave cross section to improve flexibility. The Shaping files, termed S1 and S2 have an increasing taper from their tip. S1 has a tip size of 0.17mm and a taper ranging from 2-11%, and S2 has a tip size of 0.20mm with a taper range of 4-11.5%. Shaping files are used in a brushing action with brushing directed away from the inner curve as the file is removed from the canal.

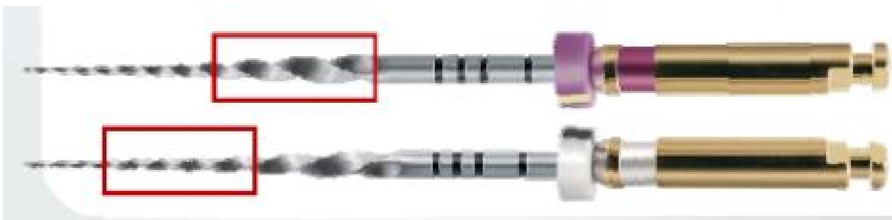

Figure 23: Shaping files and their intended cutting zone (images courtesy of Dentsply Maillefer)

Figure 23 shows S1 (purple ring) and S2 (white ring) Shaping files and illustrates the region of the file that is intended to do the greatest amount of preparation. The S1 has a slightly reduced taper compared to S2 and so prepares more coronally compared to S2 that has a wider taper and so will impart greater taper and shape more in the middle third.

The ProTaper Finishing files are designed to finish the apical third and have a fixed taper over the apical 3mm which then decreases along their length. Two sizes, termed F1 and F2, were used in this study (see Figure 24). The F1 has a tip size of 20 with a tip taper of 7% and F2 has a tip size of 25 and a tip taper of 8%. Finishing files are used in an ‘in and out’ action and must not be held at the working length once it has been reached.

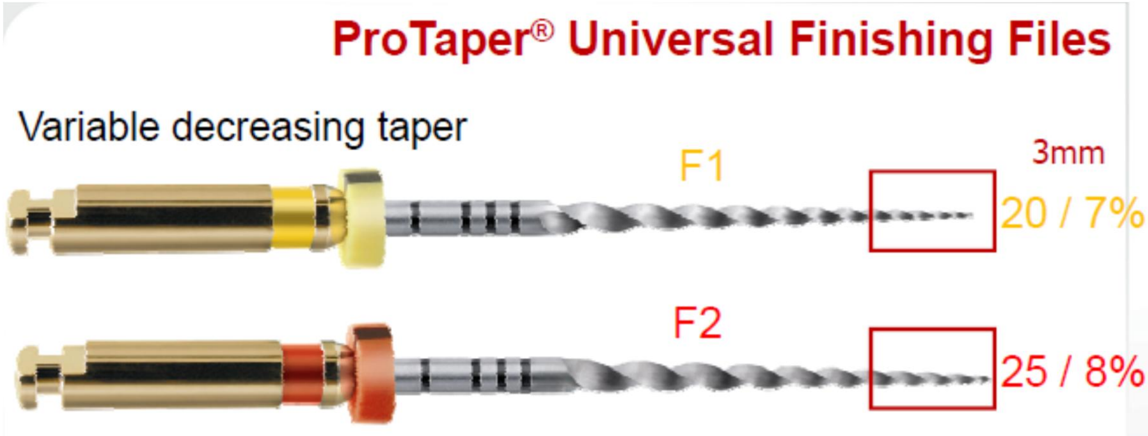

Figure 24: ProTaper Finishing files (images courtesy of Dentsply Maillefer)

6.5 Operators

The operators used in this study comprised final year undergraduate dental students from the University of Birmingham, School of Dentistry. The students had limited endodontic experience having performed less than ten endodontic treatments on patients. However, all students had received a number of skills laboratory teaching sessions in root canal therapy, which included one session using rotary nickel titanium instrumentation. These were in addition to their standard teaching to develop basic endodontic skills and understanding, such as the principles and practice of root canal therapy, and the use of stainless steel hand files and Gates Glidden burs. Students complete training exercises on both simulated root canals and extracted teeth, before being allowed to treat patients. Students are only allowed to use nickel titanium on patients once they have completed ten root canal preparations on extracted teeth.

The student operators in this investigation were undertaking an optional study module in root canal therapy to improve their skills and allow them further experience in rotary techniques.

All student operators were given detailed instruction on how to prepare the simulated root canals for this study which included:

1. A small group tutorial on the benefits and use of nickel titanium files in endodontics, to act as an overview and improve their knowledge and understanding.

2. A lecture on the procedure that they would be completing on that day with a PowerPoint presentation showing detailed step by step instructions.

3. A written protocol (Appendices A and B) for the procedure they would be completing on that day, including instructions regarding the exact lengths and sizes to prepare to, procedure and technique.

4. A video demonstrating the technique.

5. A 'live' tutor demonstration.

6.6 Motors and Set Up

Teknika electronic motors (manufactured by Dentsply Maillefer) with 16:1 ratio speed reducing handpieces were used at a speed of 300rpm for all techniques.

Figure 25: Teknika motor

6.6.1 Classical ProTaper Technique

The unit is switched on via a switch on the back of the unit. The system button is then pressed until the display reads, ' PT1 * T100 16:1 250 PTAPER S1/SX TMinMax'. The speed is set to 300rpm using the up and down buttons for rpm to change. The 'torque max' (torque maximum) button is then pressed. The handpiece is then ready for use.

6.6.2 Reciprocating Technique

The unit is switched on via a switch on the back of the unit. The speed is set to 300rpm using the up and down buttons for rpm to change. The 'CTL' (control) and 'F&R'(forward and reverse) buttons are then pressed simultaneously which selects the reciprocating action. The timing for the clockwise and anticlockwise rotation is then set to 0.09 clockwise using the up and down for torque setting buttons, and 0.05 anticlockwise using the up and down for rpm buttons. The display will read 'T.Min: esc + save, F + R Fw: 0.09 Rv: 0.05' when this is correct. The setting is then saved by pressing the 'torque min' (torque minimum) button. The handpiece is then ready for use.

6.7 Masking

Half of the canals were covered to prevent direct visualisation of the canal when it was being prepared. This was done with masking tape, with the base of the simulated canal left unmasked so that the students could see the direction of the canal curvature. An example is shown below.

Figure 26: Masked canal

6.8 Allocation of Blocks

The numbered blocks were randomly allocated between those to be prepared using the classical ProTaper technique and those using the reciprocating technique by using an online random number generator. *(http://www.mdani.demon.co.uk/para/random.htm).* Within those groups, the first half were masked and the remainder were left unmasked. The allocation was as follows, with the masked blocks shaded.

Numbers allocated to classical ProTaper group				Numbers allocated to reciprocating group		
133	97	209		66	16	36
108	80	60		78	199	79
91	62	217		195	155	145
170	220	112		14	120	6
132	135	8		194	76	173
161	121	184		221	193	58
63	158	144		83	179	115
177	50	59		4	196	46
53	104	25		15	65	105
23	47	185		148	84	152
40	5	90		189	174	163
1	190	125		33	178	77
150	164	99		219	166	72
200	154	198		39	7	54
18	187	69		61	32	86
101	204	225		21	110	172
139	149	218		89	223	96
31	116	191		206	212	109
92	215	55		11	127	48
136	131	211		201	213	171
43	186	113		141	143	26
181	35	13		114	24	167
71	126	176		197	159	67
117	27	182		157	107	3
118	68	42		151	138	210

Figure 27: Allocation of blocks

The four groups in this study were as follows:

1. Preparation using the classical ProTaper technique which were not masked.
2. Preparation by the reciprocating technique which were not masked.
3. Preparation using the classical ProTaper technique and were masked.
4. Preparation using the reciprocating technique and were masked.

The random allocation of blocks was to ensure that when analysis was completed the evaluators would not know which technique had been used to prepare the blocks.

Preparations were completed in eight sessions, with two sessions for each group. In each session the blocks were randomly allocated to the students.

6.9 Data Collected From Students

A questionnaire was designed to record information regarding the operators and their perceptions about their preparations. The level of experience was recorded according to the number of root canals they had treated clinically on patients. To be included in the study this had to be less than ten canals. The questionnaire also recorded whether or not the operators felt that they had received enough information to complete the preparations, and whether the information was easy to follow. This was scored from 1 to 10 (Lickert scale), where 1 indicated insufficient information that was difficult to understand and 10 indicated all necessary information was supplied and it was simple to understand.

The questionnaire also recorded the start and finish times for the preparations to enable assessment of the time taken for each preparation to be compared.

After completing the preparations using the two techniques, the operators were asked which method of preparation they preferred, and asked to justify this preference.

A sample of the questionnaire is included as Appendix C.

Each student was given two new sets of files. The first set was to be used to familiarise themselves and complete a practice block. The second set was to be used to prepare the blocks that would be used in the investigation.

For each technique students completed the practice block after receiving all the information regarding the preparation, as described above (see Section 6.5, above). During this time they had the option to ask questions and seek advice on any aspect they were concerned about, prior to completion of the timed and photographed blocks.

6.10 Technique One: Classical ProTaper Rotary Preparation

The working length of the block was specified at 17.5mm. This was so that both over-preparation and under-preparation could be assessed within the block's 19mm total length. A tolerance of 1mm short of this working length was judged to be acceptable, but any preparation exceeding 17.5mm was not acceptable as this would clinically be no longer within the constraints of the root canal.

Students were instructed to maintain apical patency during the technique, which involved the regular use of a size 10 stainless steel hand file set at 19mm in order to prevent debris accumulating within the block. It was recommended to use files in the presence of copious water irrigant. This was in order to help prevent procedural errors by allowing debris to be in suspension and washed out of the canal.

6.10.1 Coronal Preparation

The block was first explored with stainless steel hand files sizes 10, 15 and 20 (Flex O files (manufactured by Dentsply Maillefer)), with the tip precurved in the direction of the curve to aid negotiation. The size 10 file was placed in the canal as far as it would go without pressure and used in a watch winding motion. The length that it reached was marked on the shaft of the file using the rubber stop and this length measured and transferred to the 15 and size 20 files. These files were then taken short of this length, again using a watch winding motion. The length reached with the size

20 hand file was then transferred to the S1 and S2 ProTaper Shaping instruments. The S1 instrument was introduced into the canal rotating at 300rpm with the motor set up as described previously for the classical ProTaper technique (see Section 6.6.1). The file was used in a brushing action on the outstroke directed away from the inner curve. The file was removed and cleaned with moist gauze every five strokes, debris was removed and the file examined for damage. When the length was reached with the S1, the S2 was taken to the same point also using a brushing action to the same length. This completed the coronal preparation.

6.10.2 Apical Preparation

Students were then instructed to negotiate the canal to a working length of 17.5mm using size 10, 15 and 20 hand files having set them to the working length of 17.5mm. Beginning with the size 10, files were introduced in turn to working length using a watch winding motion. Patency was maintained from this point onwards with the size 10 set to 19mm regularly used in the presence of irrigant. Students progressed through the series until the working length had been reached with a size 20 file. Negotiation was complete when the size 20 hand file reached this length easily without pressure or rotation, but stopped at this point and did not pass further.

The ProTaper instruments were then again selected and the S1 and S2 set to the working length. Starting with the S1, these were taken to working length with regular irrigation and use of a patency file to follow the glide path created by the size 20 hand file. Again the files were regularly cleaned with damp gauze and checked for damage to the flutes. The same procedure was completed with the S2, with both files being used in a brushing action, as described previously (Section 6.4).

Apical preparation was completed using ProTaper nickel titanium rotary Finishing files F1 and F2. Both of these files were set to working length. The F1 was first passively placed into the canal. If the distance from the rubber stop to the top of the block was more than 2mm, then more coronal preparation was required, and the students instructed to repeat coronal preparation with the S2 rotary file with brushing on the outside of the curve on withdrawal, before continuing with the F1. If it was less than 2mm, then the students could continue apical preparation. This was to check the coronal preparation was sufficient and so reduce the incidence of procedural errors with the Finishing files. The F1 was used first and introduced into the canal again at a speed of 300rpm, with the motor set up as for the Shaping files. The file was taken to working length with no brushing. As soon as the file reached the predetermined length of 17.5mm, it was withdrawn and the canal irrigated and a patency file used. This was then repeated with the F2. This completed the preparation. Timings were recorded and the questionnaire completed.

6.11 Technique Two: Reciprocating Preparation

For this technique the students needed only the stainless steel hand files sizes 10, 15 and 20 and the F2 rotary ProTaper Finishing file. Again the students were instructed to use regular irrigation and a patency file after establishment of working length.

6.11.1 Negotiation

The stainless steel hand files were used in the same manner as the other techniques to explore the canal. This involved using the precurved size 10 to as far as it would go without pressure using a watch winding motion and marking this length on the file using the rubber stop. This length was transferred to the 15 then size 20 files, again precurved, and these were taken to this length as before. The 10, 15 and 20 hand files were then all set to working length at 17.5mm. Starting with the size 10 file these were all taken to working length using a watch winding motion with regular irrigation. Negotiation was complete when the student could easily pass the size 20 hand file to length with resistance felt at that length, but without the file passing any further.

6.11.2 Preparation

The motor was set up by the instructor for the specific reciprocating settings as detailed in the motors and set up section above (Section 6.6.2). An F2 ProTaper file was set at 17.5mm using the rubber stop, and introduced into the canal at 300rpm in the reciprocating mode with a gentle picking action. The file was cleaned and inspected every five times it was advanced using moist gauze to ensure debris removal and no damage to the file had occurred. This process was repeated until the working length had been reached. At this point the preparation was complete and timings recorded and the questionnaire filled in.

When instrumenting the masked blocks, the students were told that as the blocks were only masked around the outside, and not on the bottom end, they could see which way the canal curved. This gave the advantage of knowing the direction of the curve, and made hand instrumentation more predictable as hand files could be gently pre-curved before being introduced into the canal, thus making the curve easier to negotiate and instrument.

6.12 Post Preparation Image Recording

Following completion of canal instrumentation, the block was re-photographed using the model system of fixed camera and fixed metal location device to ensure accurate replacement and subsequent image superimposition.

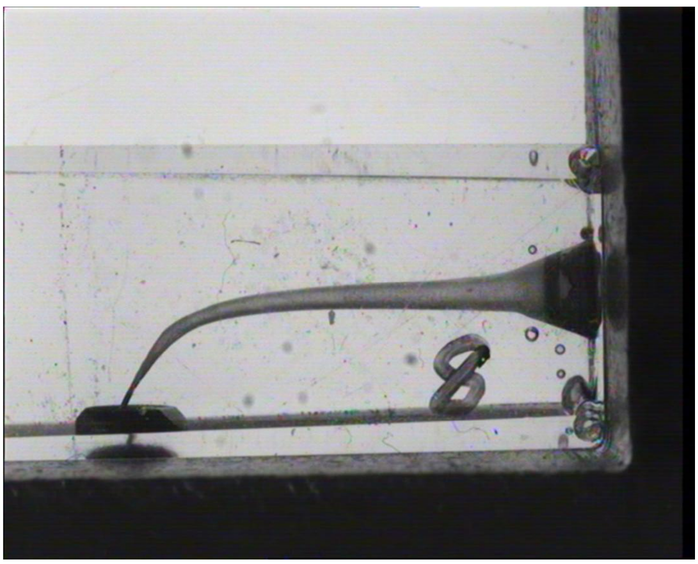

Figure 28: Post preparation image

6.13 Analysis and Scoring of Images

The pre and post preparation images were superimposed using Adobe Photoshop cs3, and a measuring grid specifically developed for this study was overlaid to allow comparison of the preparations and measurement of canal transportation in four locations. The grid was drawn using Adobe Photoshop using concentric circles spaced 0.5mm apart as determined from an endodontic ruler and imported into the software. The layering function was used to superimpose the circles over the ruler to ensure they were the correct dimensions apart and so could be used in the results. The circles layer was then placed over the pre and post preparation images with the '0' targeted over the end of the simulated canal so that distance along the canal could be easily identified. An example is shown below.

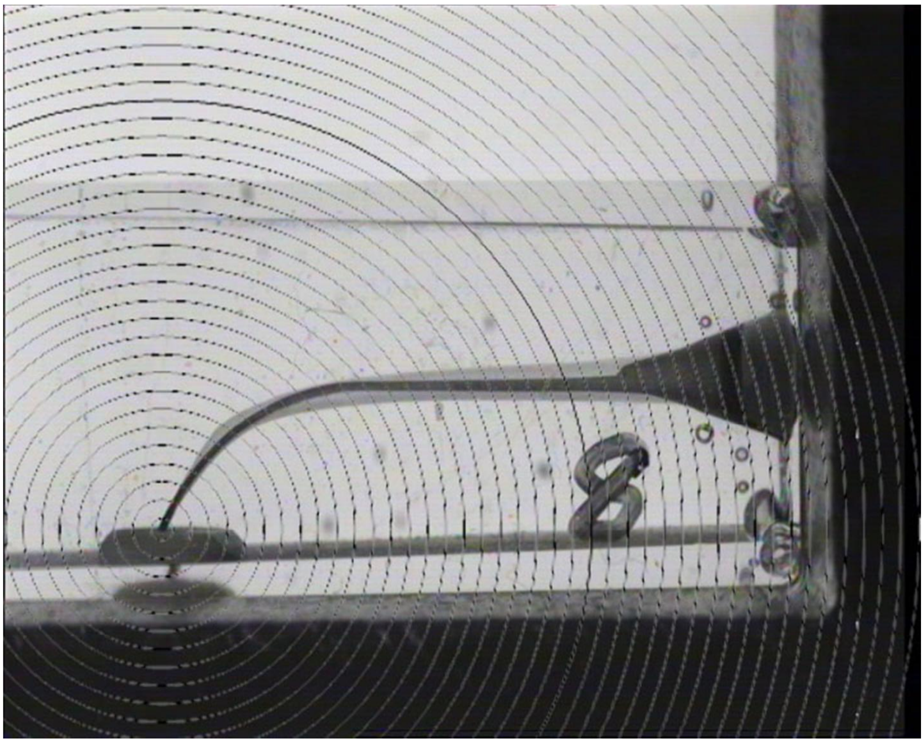

Figure 29: Layered post and pre preparation image with concentric circles

The images were printed on a photo printer (Epson Stylus Photo inkjet) on high quality paper (Jessops double sided ink jet paper – 170gsm).

The preparations were analysed according to Schilder's mechanical objectives of canal preparation by two independent examiners.

These mechanical objectives were:

- Original anatomy maintained
- Canal gets narrower as the canal progresses to its terminus
- Canal has a continuous smooth progressive taper
- The end of the canal must be in its original position and not moved
- The end of the canal must be as small as practical and not over enlarged

The preparations were also analysed to see if the following had occurred:

- Coronal over-preparation
- Apical over-preparation
- Ledge formation and its location

The images were arranged into numerical order rather than technique order, so that the examiners would not know which technique had been used to complete the preparation and thus eliminate risk of bias. The results were analysed independently by the two examiners and assessed against the agreed criteria. Results were entered into a grid in a Microsoft Excel spreadsheet with an entry of '1' indicating the canal preparation objective had been met, and '2' indicating it had not. After all the images had been independently evaluated, a meeting was held to assess the level of inter examiner agreement and any disagreements resolved. The extent of inter examiner agreement is shown overleaf in Figure 25. The preparations where there was disagreement were assessed by looking at examples of preparations that clearly met and did not meet the criteria, and then agreeing which they were most similar to, and coming to a consensus.

Interexaminer Agreement Results – Extent of disagreement	
Criteria	**Number of disagreements**
Continuous taper	0 disagreements
Original anatomy maintained	2 disagreements (1.1%)
Narrower as you go apical	3 disagreements (1.68%)
Foramen as small as is practical	2 disagreements (1.1%)
Foramen in its original position	1 disagreement (0.6%)
Overprepared coronally	9 disagreements (5.03%)
Overprepared apically	9 disagreements (5.03%)
Ledged	1 disagreement (0.6%)

Figure 30 – Extent of inter-examiner disagreement

The degree and direction of canal transportation was measured by analysing the images at intervals of 1mm, 3mm, 5mm and 7mm from the specified working length. The distance from the edge of the pre-preparation image to the post preparation image was measured on both inner and outer walls of the canal. This was done using an endodontic ruler with calibrations at 0.1mm under magnification. An example is shown in Figure 31, overleaf.

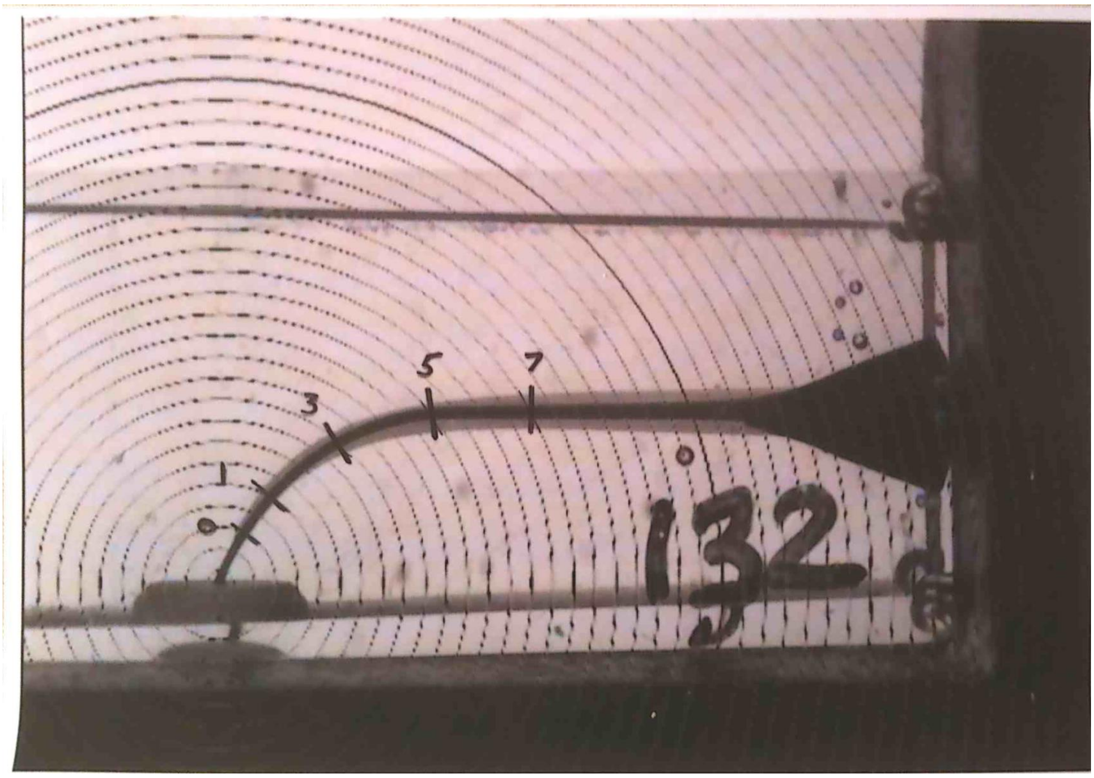

Figure 31: Working length (0), 1, 3, 5 and 7mm locations for measuring canal transportation

These results were entered into a Microsoft Excel spreadsheet. The mean value for the amount of removal of material at these points was calculated along with the standard deviations and the results entered into a table.

6.14 Statistical Analysis

Statistical analysis was undertaken using Minitab (version 14). The groups were compared using non-parametric Mann Whitney tests to see if there were any significant differences between the groups.

Further statistics were done to analyse the proportions of preparations that met the Schilder criteria between the groups by performing confidence interval tests (Wilson method) using Confidence Interval Analysis Software version 2.1.2.

The percentage of preparations that met each individual criterion was calculated for each of the groups and entered into a table. The percentage of preparations that met all of the five Schilder criteria was also calculated and entered into a table.

The data for the times taken to complete the preparations was analysed by recording the length of time for each block in minutes and calculating the mean time taken for each of the four groups described above (Chapter 6 page 122). As this data failed a Shapiro-Wilk normality test ($P < 0.05$), a Kruskal-Wallis non parametric one way ANOVA test on ranks was performed to see if there were any significant differences in the times between the groups.

6.15 List of References

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7 Results

7.1 Overview

The study compared the classical ProTaper technique using four files with the reciprocating technique using one file. For both techniques, the final preparation file was the same. Preparations were completed using simulated canals that were either unmasked, and so the operator could see the canal, with no tape obscuring the canals (“no tape”), or masked with tape to more realistically simulate the clinical situation, where the clinician cannot see the file progressing down the canal or the canal curvature (“tape used”). The summary results are presented in Table 1.

Table 1: Summary results				
Technique:	**Classical ProTaper**	**Reciprocating**	**Classical ProTaper**	**Reciprocating**
	no tape	**no tape**	**tape used**	**tape used**
Percentage of preparations that met all five criteria	47%	34%	77%	44%

Figure 32: Table 1 – Summary results

Schilder’s mechanical criteria for an ideal preparation may be summarised as follows:

- The original anatomy maintained.
- The canal gets narrower as the canal progresses to its terminus.
- The canal has a continuous smooth progressive taper.

- The end of the canal must be in its original position and not moved.
- The end of the canal must be as small as practical and not over enlarged.

The results demonstrated that the classical ProTaper technique was more likely to produce a preparation that met Schilder's five mechanical criteria for ideal canal preparation compared to the reciprocating technique, whether or not the canal was obscured.

7.2 Comparison of Techniques Without Tape

The results showed that it was more likely that a preparation meeting all Schilder's criteria would be produced when using classical ProTaper technique (occurring in 47% of preparations) than when using the reciprocating technique (34%). Examples of preparations meeting all of the criteria are shown below.

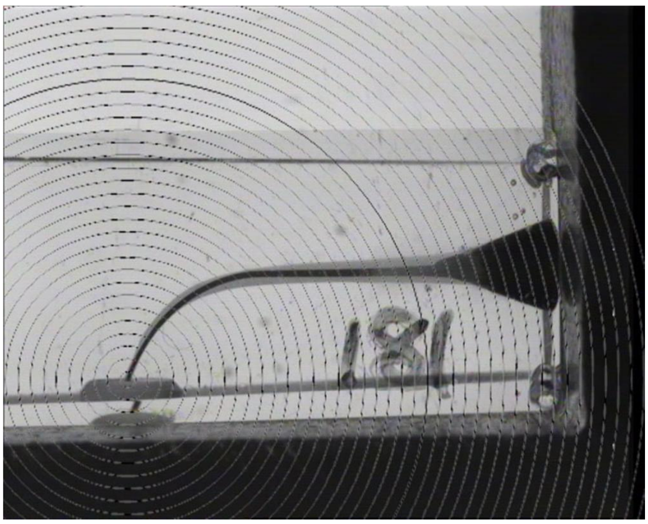

Figure 33: All criteria met using classical ProTaper technique without tape

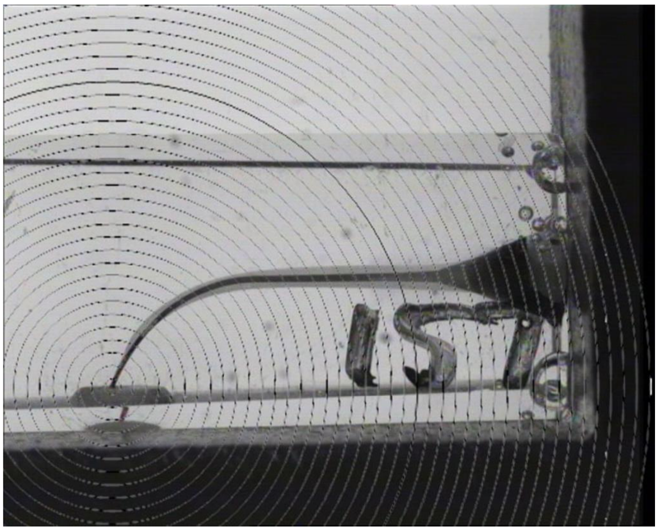

Figure 34: All criteria met using reciprocating technique without tape

7.2.1 General Observations and Measurements

There were no statistically significant differences in any of Schilder's criteria for the no tape groups at the 95% confidence level, or the statistically weaker 90% level (Mann-Whitney and confidence interval tests). This is shown in Table 2, overleaf. In this case, a p-value of 0.05 or less indicates that the result is statistically significant at the 95% confidence level.

Table 2: Detailed results of the Mann-Whitney tests								
p-values	**Continuous taper**	**Original anatomy maintained**	**Narrower as go apically**	**Foramen small as practical**	**Foramen in original position**	**Over- prepared coronal**	**Over-prepared apical**	**Ledged**
Classical ProTaper no tape vs. reciprocating no tape	0.6310	0.2162	0.4600	0.9238	0.7627	Computation not possible	0.2909	0.2111
Classical ProTaper tape used vs. reciprocating tape used	0.0566	0.0135	0.0061	0.0591	0.1095	0.9075	Computation not possible	0.0135
Classical ProTaper tape used vs. classical ProTaper no tape	0.2427	0.4861	0.1641	0.0153	0.558	0.4347	0.1078	0.6569
Reciprocating tape used vs. reciprocating no tape	0.6599	0.4093	0.3656	0.8018	0.6687	Computation not possible	0.5114	0.2931

Key:

(red)	Statistically significant at the 95% confidence level
(yellow)	Statistically significant at the 90% confidence level

Figure 35: Table 2 – Detailed results

Table 3: Detailed results - percentage of preparations meeting individual criteria									
	Continuous taper	**Original anatomy maintained**	**Narrower as go apically**	**Foramen small as practical**	**Foramen in original position**	**Over-prepared coronal**	**Over-prepared apical**	**Ledged**	**Ledges outside working length tolerance**
	%	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
No tape									
Classical ProTaper no tape	71	76	68	47	58	3	34	13	22
Reciprocating no tape	66	63	60	49	54	0	23	33	53
Tape used									
Classical ProTaper tape used	83	83	83	77	80	7	17	17	29
Reciprocating tape used	60	52	48	52	60	4	16	46	33

Figure 36: Table 3 – Detailed results - percentage of preparations meeting individual criteria

7.2.2 Key Findings

The key findings from the results summarised in Table 3 are as follows:

- Table 3 shows that most preparations had a continuous taper, with 71% of the classical ProTaper preparations and 66% of those prepared using the reciprocating technique meeting this criterion.
- The classical ProTaper technique maintained canal anatomy 76% of the time compared to 63% for the reciprocating technique, indicating better maintenance of the original canal shape for the classical ProTaper technique, although not at a statistically significant level.
- The canal was narrower as it went apically in 68% of classical ProTaper preparations compared to 60% for reciprocating preparations.
- The apical region contained the greatest number of errors for both groups with 47% of classical ProTaper and 49% of reciprocating preparations keeping the foramen as small as practical, and 58% of classical ProTaper and 54% of reciprocating preparations keeping the foramen in its original position.
- Over-preparation in the apical region occurred in 34% of classical ProTaper canals and 23% of reciprocating preparations.

Figure 37, overleaf, is an example of procedural errors in the apical region.

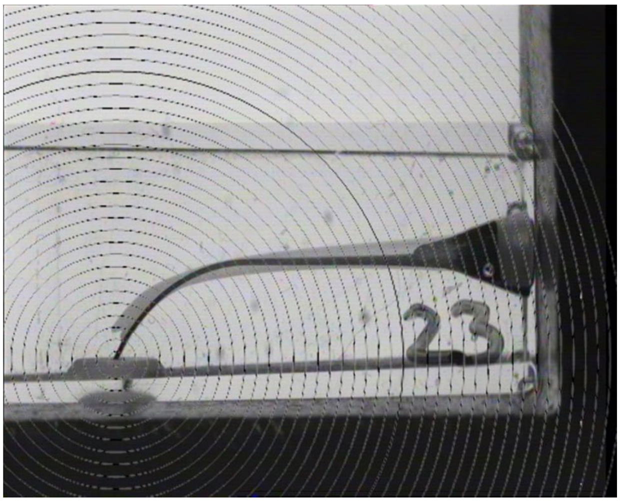

Figure 37: Loss of anatomy and not becoming narrower as you go apical and ledge formation with classical ProTaper technique

Over-preparation coronally was minimal with only one canal over-prepared using the classical ProTaper technique (see Figure 38) and none with the reciprocating technique.

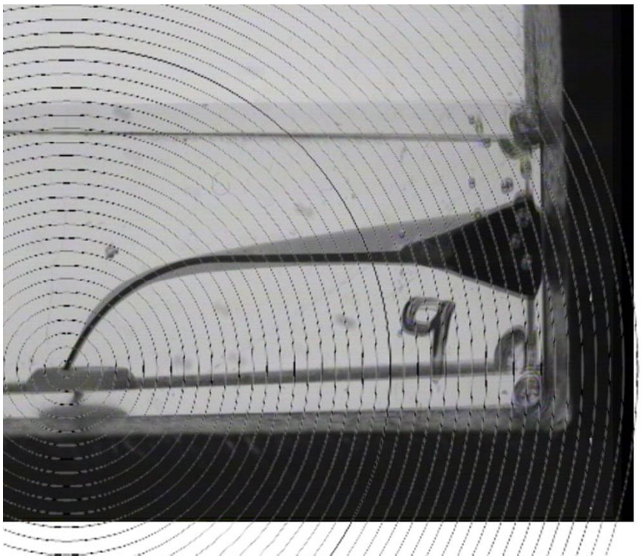

Figure 38: Coronal over-preparation with classical ProTaper

Table 4: Average material removal measured at four distances from the apex								
Position on curve from apex	**1mm outside**	**1mm inside**	**3mm outside**	**3mm inside**	**5mm Outside**	**5mm inside**	**7mm outside**	**7mm inside**
Mean								
Classical ProTaper no tape	0.21	0.03	0.16	0.14	0.07	0.35	0.26	0.23
Reciprocating no tape	0.20	0.01	0.19	0.11	0.09	0.31	0.26	0.21
Classical ProTaper tape used	0.15	0.06	0.13	0.17	0.05	0.38	0.26	0.27
Reciprocating tape used	0.24	0.03	0.17	0.16	0.05	0.38	0.24	0.26
Standard deviation								
Classical ProTaper no tape	0.12	0.05	0.09	0.10	0.05	0.12	0.08	0.07
Reciprocating no tape	0.10	0.03	0.08	0.08	0.05	0.10	0.06	0.06
Classical ProTaper tape used	0.15	0.06	0.07	0.08	0.05	0.06	0.09	0.07
Reciprocating tape used	0.18	0.05	0.16	0.08	0.05	0.10	0.08	0.09

Figure 39: Table 4 - Average material removal measured at four distances from the apex

The key findings from the results summarised in Table 4 are as follows:

- Table 4 shows that the greatest amount of removal of canal material was on the inside of the curve 5mm from the apex for both techniques, with the reciprocating technique removing less at 0.31mm compared to 0.35 for classical ProTaper. Overall, the reciprocating technique was the more conservative technique removing slightly less material at all levels measured, apart from at 3mm on the outside of the curve where the reciprocating technique removed 0.14mm compared to 0.11 for classical ProTaper.
- Table 4 also shows that the largest standard deviations around the mean were at 5mm from the apex on the inside of the curve, and 1mm from the apex on the outside of the curve. This shows that there was the greatest variation in recorded results at these measurement levels, and that more material was removed on the outside of the curve apically and inside of the curve more coronally.
- At 2.5mm from the apex there were a number of ledges created with the reciprocating technique, which is reflected in the greater removal at this level on the outside of the curve at 3mm. Classical ProTaper produced less ledges with a 13% incidence compared to 33% for reciprocating preparations. The ledges for classical ProTaper were also mostly (78%) distributed within 1mm of the apex of the canals and so were within the tolerance of acceptable working length. In comparison, 53% of the ledges produced when using the reciprocating technique were outside the 1mm tolerance, and concentrated around 2mm - 2.5mm from the apex.

Overleaf are examples of ledge formation outside the working length tolerance.

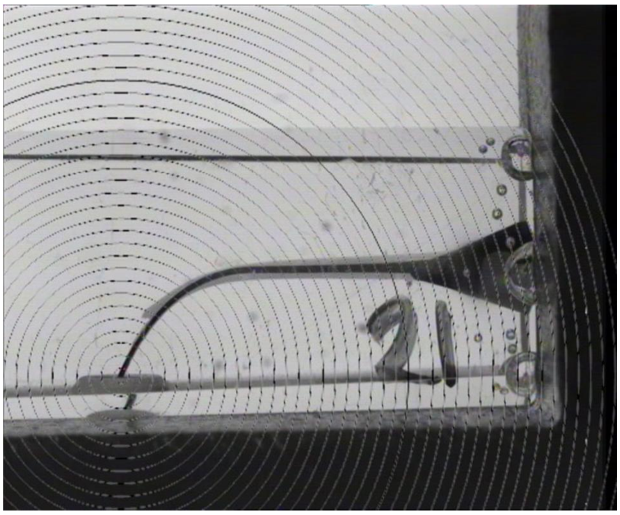

Figure 40: Ledge formation more than 1mm from the specified working length using the reciprocating technique with no tape

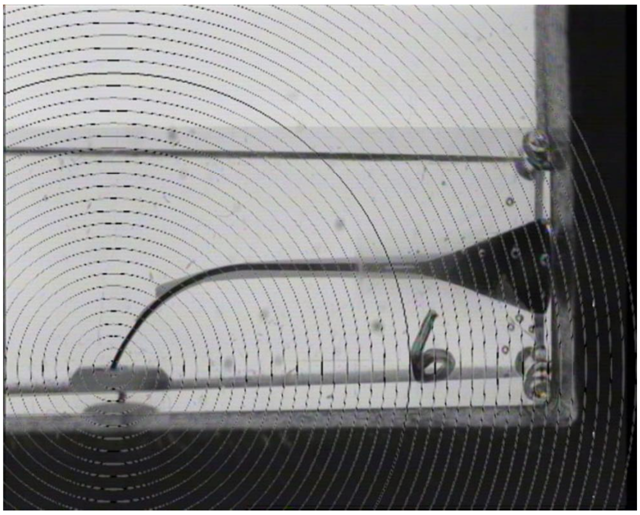

Figure 41: Ledge formation 2.5mm from the specified working length using the reciprocating technique with tape used

7.2.3 Mean Values – Descriptive Data

For each criterion described by Schilder, the results were assessed and assigned a notation of 1 to a positive outcome (that is, the criterion has been met), and a notation of 2 to a negative outcome (that is, the criterion had not been met). Notations were assigned as follows in respect of three further criteria that were considered:

Notation assigned	**Yes**	**No**
Was the canal over-prepared coronally?	1	2
Was the canal over-prepared apically?	1	2
Was there a ledge?	1	2

Figure 42: Assigned notations

Using these assigned notations, the mean value of the results was calculated, and summarised in Table 5. In respect of each of Schilder's five criteria the higher the value in the first five columns of Table 5, the higher the incidence of errors occurring and the criteria not being met. In respect of the three further criteria, the higher the value in the final three columns of Table 5, the *lower* the incidence of errors.

Table 5 shows there were few differences in the results for the reciprocating technique compared to classical ProTaper.

Table 5: Mean values for the assessed criteria

	Continuous taper	Original anatomy maintained	Narrower as go apically	Foramen small as practical	Foramen in original position	Over-prepared coronal	Over prepared apical	Ledged
No Tape								
Classical ProTaper no tape	1.28	1.24	1.32	1.52	1.42	1.97	1.66	1.79
Reciprocating no tape	1.34	1.37	1.40	1.51	1.45	2.00	1.77	1.66
Tape Used								
Classical ProTaper tape used	1.16	1.16	1.16	1.23	1.20	1.90	1.80	1.80
Reciprocating tape used	1.40	1.48	1.52	1.48	1.40	1.96	1.84	1.52

Figure 43: Table 5 - Mean values for the assessed criteria

Similar mean values for keeping the foramen as small as practical of 1.52 for classical ProTaper and 1.51 for the reciprocating technique indicate the high incidence of procedural errors in both sets of data.

Lower mean values for maintaining the original anatomy of 1.24 for classical ProTaper and 1.37 for the reciprocating technique indicate fewer errors for the classical ProTaper technique.

Mean values for the incidence of ledges of 1.79 for classical ProTaper compared to 1.66 for the reciprocating technique indicate a greater incidence of ledges for the reciprocating technique.

7.3 Comparison of Techniques With Tape Used

Table 1 shows that it was more likely that a preparation meeting all five criteria according to Schilder was met when the classical ProTaper technique was used (77%) compared with the reciprocating technique (44%). This is consistent with the findings when no tape was used. Examples are shown below.

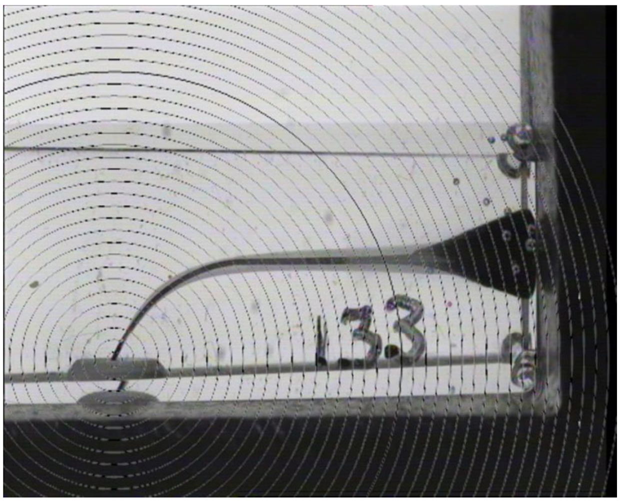

Figure 44: Preparation meeting all criteria using classical ProTaper technique with tape used

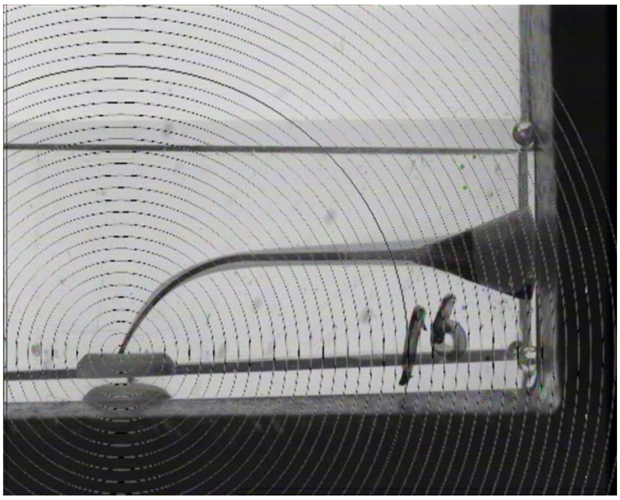

Figure 45: Preparation meeting all criteria using the reciprocating technique with tape used

7.3.1 General Observations and Measurements

There were a number of statistically significant differences between the two techniques at the 95% confidence level (Table 2). These included maintaining the original anatomy (p=0.0135), the canal becoming narrower as the preparation went apically (p=0.0061) and in the incidence of ledges (p=0.0135). These results are summarised in Table 2. In all of these cases the classical ProTaper technique produced less errors and a greater number of preparations that met the criteria.

These results are supported by the confidence interval tests. For the criterion 'original anatomy maintained' the proportion of classical ProTaper blocks with tape used which met the criterion standard (score = 1) was 0.833 and for reciprocating with tape used was 0.520 with a difference between the two proportions of 0.313. The 95% confidence for the difference between the two population proportions according to the recommended method is 0.067 to 0.512. The standard error of the difference is 0.121. Although the best estimate of the difference in proportions between classical ProTaper with tape used and reciprocating with tape used yielding a score of 1 for original anatomy maintained is 31%, the 95% confidence interval ranges from 7% to 51%, demonstrating a statistically significant difference. There was also a statistically significant difference for the criterion ‘narrower as you go apically’. The proportion of classical ProTaper tape blocks which met the criterion standard (score = 1) was 0.833 and for reciprocating with tape used was 0.480 with a difference between the two proportions of 0.353. The 95% confidence for the difference between the two population proportions according to the recommended method is 0.103 to 0.556. The standard error of the difference is 0.121. Although the best estimate of the difference in proportions between classical ProTaper with tape used and reciprocating with tape used yielding a score of 1 for narrower as you go apical is 35%, the 95% confidence interval ranges from 10% to 56% demonstrating a statistically significant difference. There were no other statistically significant results for the tape used groups using this method for the other three criteria.

Table 2 shows that there were statistical differences in producing a continuous taper (p=0.566) and keeping the foramen as small as practical (p=0.0591), but at the statistically weaker 90% confidence level. In these instances, again the classical ProTaper technique produced preparations that met the criteria in a greater number of instances.

Table 3 shows that the classical ProTaper preparations produced a continuous taper in 83% of the preparations compared with 60% for reciprocating preparations, and maintained the anatomy better in 83% of the preparations compared with 52% for reciprocating. 48% of reciprocating preparations were narrower as they progressed apically compared with 83% for classical ProTaper. In the apical region, classical ProTaper again performed better, keeping the foramen as small as practical more frequently (77% *versus* 52%) and keeping the foramen in its original position more consistently (80% *vs*. 60%). The incidence of over-preparation apically was low with an incidence of just 17% for classical ProTaper and 16% for reciprocating. An example is shown overleaf.

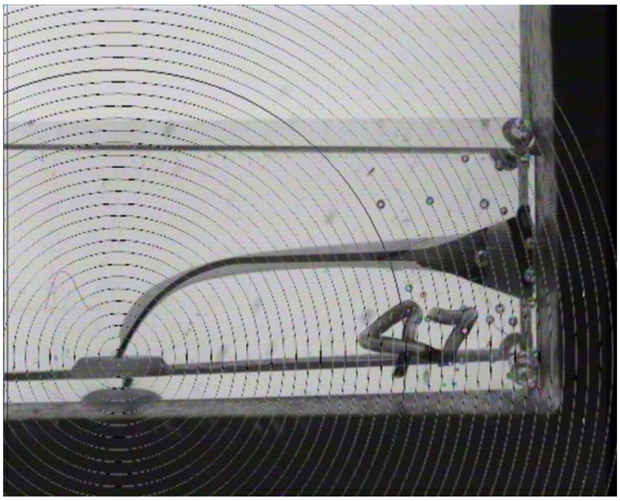

Figure 46: Apical over-preparation with classical ProTaper technique with tape used

There were only two instances of coronal over-preparation for classical ProTaper, and five for reciprocating. Table 4, shows that the greatest amount of material removed during preparation was at 5mm from the apex on the inside of the curve, with both techniques removing an average of 0.38mm. Again there were few differences in the average amount removed at most of the other sites measured with the reciprocating technique removing slightly less material. This was not the case on the outside of the curve at 1mm and 3mm, where the reciprocating technique removed more material (1mm from the apex: 0.15mm vs. 0.24mm and 3mm from the apex: 0.13mm vs. 0.17mm).

Table 4 also shows that the greatest variation in results arose at 1mm from the apex on the outside of the curve for both techniques, as the standard deviation was 0.15 for classical ProTaper technique and 0.18 for the reciprocating technique. Considerable variation also occurred for the reciprocating technique at 3mm on the outside of the curve (with a standard deviation of 0.16).

Table 3 shows that the incidence of ledges was greater with the reciprocating technique (46% incidence), which again produced a number of ledges at the 2mm - 2.5mm from the specified working length, compared to classical ProTaper that had most of the ledges (17% incidence) located within the 1mm from the apex tolerance for working length (71%). An example of the latter is shown below.

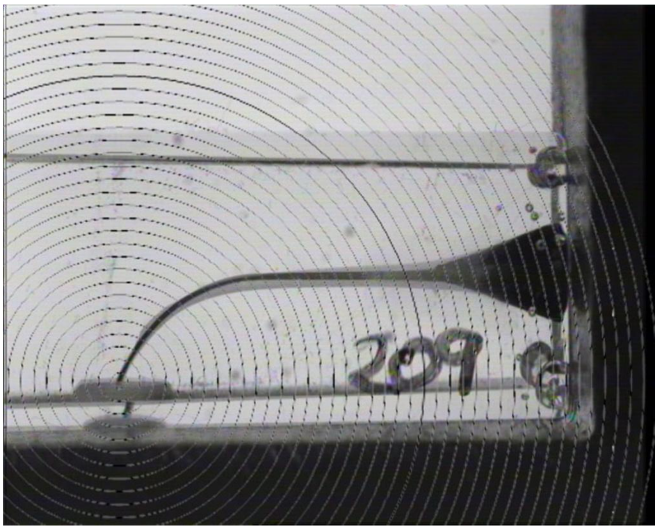

Figure 47: Classical ProTaper preparation with tape used demonstrating a ledge within 1mm of the specified working length

There was one incidence of a fractured instrument with the reciprocating technique (see Figure 48, overleaf).

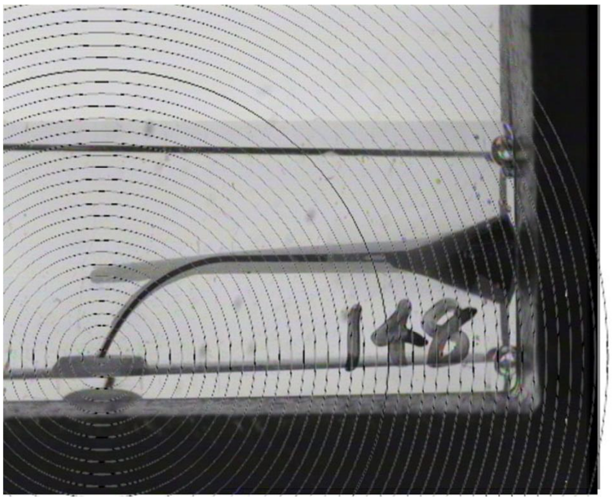

Figure 48: Reciprocating preparation with anatomy not maintained. This was due to file fracture in the apical region, followed by its reintroduction without the operator realising it had fractured. The fracture removed the safe end of the file resulting in a sharp cutting tip which will not negotiate the curve

7.3.2 Mean Values: Descriptive Data

As explained earlier, notations were assigned to the eight criteria that we used to assess the preparations and the averages of these values are set out in Table 5.

The descriptive values demonstrated greater procedural errors and an increased likelihood of not meeting Schilder's five criteria for the reciprocating technique compared with classical ProTaper (refer to Table 5). The greatest differences between the techniques occurred in respect of the incidence of canals becoming narrower as the canal went apically (an average 1.16 for classical ProTaper and 1.52 reciprocating), and in the incidence of maintaining the original anatomy of the canal (1.16 for classical ProTaper and 1.48 for reciprocating). This demonstrated a higher occurrence of errors with the reciprocating technique for both criteria.

7.4 Comparison of Techniques With and Without Tape Masking The Canals

7.4.1 Classical ProTaper

The results demonstrated that the classical ProTaper technique with tape masking the canal was more likely to produce a preparation that met Schilder's five criteria for ideal canal preparation than when the operator could see it. Table 1 demonstrates that 77% of masked preparations met all five criteria compared with 47% of unmasked preparations.

7.4.1.1 General Observations and Measurements

Considering Schilder's criteria individually, the only statistically significant difference (p=0.0153) between the masked and unmasked groups was in keeping the foramen as small as practical. Table 2 shows that the foramen was kept as small as practical in a greater number of cases if the canal was masked and the operator could not see it.

These results are supported by the confidence interval tests. For the criterion 'foramen as small as practical' the proportion of classical ProTaper blocks with no tape used which met the criterion standard (score = 1) was 0.474 and for classical ProTaper with tape used was 0.767, with a difference between the two proportions of -0.293. The 95% confidence for the difference between the two population proportions according to the recommended method is -0.481 to -0.059. The standard error of the difference is 0.112. Although the best estimate of the difference in proportions between classical ProTaper with no tape used and classical ProTaper with tape used yielding a score of 1 for original anatomy maintained is 29%, the 95% confidence interval ranges from 6% to 48%, demonstrating a statistically significant difference. There were no other statistically significant results for tape used versus no tape masking the canals for the other four criteria using this method.

In respect of the four other criteria, the results were not statistically significant, but, in general the results showed that the criteria were more likely to be met when tape masked the canals, as follows:

- The canal had a continuous taper in 83% of preparations where there was tape masking the canals compared with 71% where there was none.
- The original anatomy was maintained in a greater number of cases (83% of preparations versus 76%).
- The canal was narrower as it went apically in 83% of masked preparations compared to 68% when no tape was used.
- Apically, the foramen was in its original position in a greater percentage of preparations (80% of preparations versus 58%), and there was less apical over-preparation where tape masked the canals.

An example of apical over-preparation is shown below.

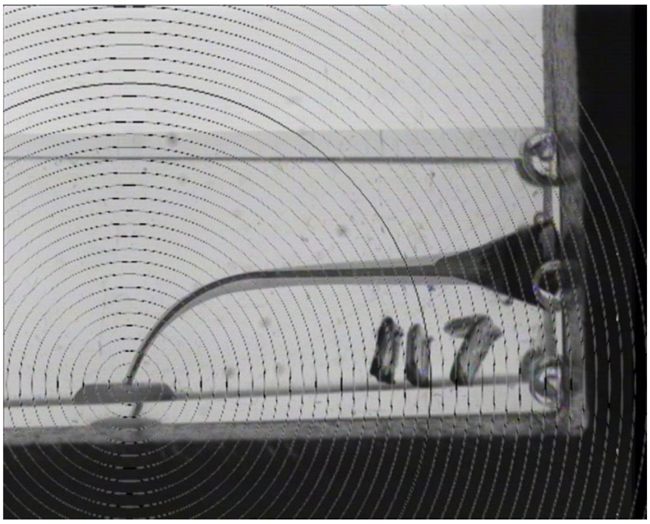

Figure 49: Apical over-preparation and the foramen not as small as practical with classical ProTaper technique and no tape masking the canal

As shown in Table 4, where tape was used, there was a slightly greater, but not significant (so $P > 0.05$) amount of removal on the inside of the curve, and less on the outside of the curve, illustrating a reduced effect of the file straightening within the canal as it prepared.

Table 4 shows that there were a similar number of ledges created whether or not the canal could be seen by the operator. Of the ledges created, the majority were within 1mm of the apex and therefore within tolerance of working length, regardless of whether the canals were masked or not.

There were few differences in the values for standard deviation between the preparations where the canals were masked and those that were not. The greatest difference was at 5mm distance from the apex on the inside of the curve, with the greater value being for preparations where the canal was not masked with tape, demonstrating greater variation in results at this level.

7.4.1.2 Mean Values: Descriptive Data

As explained earlier, notations were assigned to the eight criteria that were used to assess the preparations and the averages of these values are set out in Table 5.

For all of Schilder's five criteria, where no tape masked the canals the average values were higher compared to the equivalent masked preparations. This indicates a higher incidence of not meeting the criteria.

Table 5 also shows the mean values in respect of coronal over-preparation and ledges. Values of 1.90 for the masked preparations and 1.97 for unmasked demonstrate a very low incidence of coronal over-preparation, and values of 1.80 for masked and 1.79 for unmasked demonstrate very similar incidences of ledges.

7.4.2 Reciprocating Technique

The results demonstrated that the reciprocating technique with tape masking the canal was more likely to produce a preparation that met Schilder's five criteria for ideal canal preparation than when the operator could see it. Table 1 demonstrates that with tape masking the canal 44% of preparations met Schilder's criteria, whereas only 34% of unmasked preparations met the criteria.

7.4.2.1 General Observations and Measurements

Table 2 shows that there were no statistically significant differences between groups in respect of whether the preparations met Schilder's five criteria or the other further criteria whether or not tape was used to mask the canals.

Considering Schilder's criteria individually, there was very little difference in whether the taper of the canal was continuous, with 66% of not masked and 60% of masked preparations meeting that criterion (see Table 3). Table 3 also shows that the original anatomy was maintained, and the canal narrower as it went apically in a greater percentage of preparations with no tape masking the canals. Apically, the foramen was as small as practical and kept in its original position in a higher percentage of preparations where there was tape masking the canals.

There was generally less removal of material on the inside of the curve where no tape masked the canal, and very little difference on the outside, as shown in Table 4.

There was a higher incidence of ledges where tape masked the canal with a 46% incidence compared to a 33% incidence where there was no tape masking the canals. However, of the ledges created, there was a higher percentage outside the 1mm from the apex tolerance of working length with the no tape group (53%) than the tape used group (33%). An example is shown overleaf

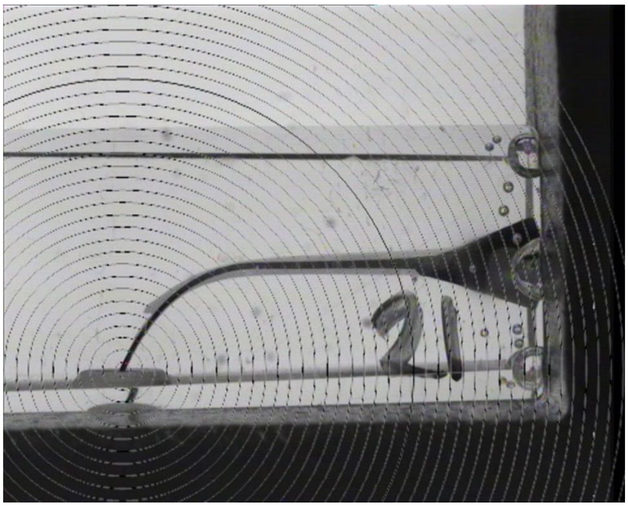

Figure 50: Ledge formation outside the 1mm working length tolerance using the reciprocating technique with no tape masking the canal

As demonstrated in Table 4, the greatest differences in values for standard deviation between the groups were at 3mm and 1mm from the apex on the outside of the curve. Where tape masked the canals the values were higher, indicating a greater variation in results at this distance. Values at the other distances were very similar for both sets of data.

7.4.2.2 Mean Values: Descriptive Data

As explained earlier, notations were allocated to the eight criteria that we used to assess the preparations, and the means of these values are set out in Table 5.

There were no instances of coronal over-preparation where no tape masked the canal, as shown by a value of '2' for this group in Table 5. A value of 1.96 for masked canals indicates a very low incidence for this group too.

There was a lower likelihood of apical over-preparation where tape was used (a mean of 1.84 versus 1.77), but a greater incidence of ledges (1.66 versus 1.52). There were no statistically significant differences in the data for the two groups for any of the additional criteria.

7.5 Questionnaires

7.5.1 Information Regarding the Techniques

An example of the questionnaire is included as Appendix C. The operators were asked whether they felt that they had received enough information to complete the preparations, and whether the instructions were easy to follow. The operators scored this from 1, where there was insufficient information and the questionnaire was difficult to understand, to 10 where all the necessary information was supplied and it was simple to understand. An average score of 9.62 regarding the amount of information and 9.07 regarding how easy the questionnaire was to follow demonstrated that there was sufficient information and it was very easy for the operators to understand.

7.5.2 Time Taken to Complete the Canals

The amount of time to prepare each canal was recorded by the operators, and entered into the questionnaire. The means are shown in the table below.

Table 6: Average preparation times

	Classical ProTaper	Reciprocating
no tape	12.57 minutes	11.05 minutes
tape used	13.84 minutes	12.27 minutes

Figure 51: Table 6 - Average preparation times

Table 6 shows that the fastest method of preparation was using the reciprocating technique with no tape masking the canal. Whether or not tape obscured the canal, the reciprocating technique was the faster, and whichever technique was used, both proved faster where the operator could see the canal and it was not masked with tape. Figure 52 shows the results of the statistical test on ranks for the times taken to prepare the canals for all groups. The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.359). However, the data does demonstrate a trend of increased time for the classical ProTaper technique compared with reciprocating, and also for blocks with tape used compared with unmasked blocks. Although these results are not at a statistically significant level, the trends may have proved significant if a larger sample size was used.

Table 7 – Statistical analysis of the time taken to prepare canals

(Results of Kruskal-Wallis non parametric one way ANOVA test on ranks)

Group	**Number**	**Missing**	**Median** *(minutes)*	**25%** *(minutes)*	**75%** *(minutes)*
<u>no tape</u>					
Classical ProTaper	23	0	13.000	8.000	15.000
Reciprocating	21	0	10.000	8.000	15.000
<u>tape used</u>					
Classical ProTaper	25	0	13.000	10.000	16.000
Reciprocating	26	0	10.000	8.750	15.750

H = 3.220 with 3 degrees of freedom. (P = 0.359)

Figure 52: Table 7 - Statistical analysis of the time taken to prepare canals (results of Kruskal-Wallis non parametric one way ANOVA test on ranks)

7.5.3 Operator Preferences

The operators were asked after they had completed both techniques which one they preferred. The results were entered into the questionnaire. 88% of operators chose the reciprocating technique. The comments on why this option was preferred regarded the speed and simplicity of the technique. One commented that they preferred the reciprocating technique, but were aware that they had created ledges, and one made the comment that they preferred it, but would like to see evidence for its superiority. The few operators who preferred ProTaper (12%) commented that they felt they created less errors, the system seemed more forgiving, and the result was better with this technique.

8 Discussion

8.1 Introduction

The first aim of this study was to evaluate the differences in preparing simulated root canals using two different preparation techniques: the classical ProTaper technique using four files and the reciprocating technique using a single ProTaper file.

The classical ProTaper technique uses variable taper Shaping and Finishing files to the working length of the preparation in an electric torque sensing motor at 300rpm in a continuously rotating motion. The design of the flutes together with a triangular cross section is claimed to remove dentine efficiently. The flexibility of nickel titanium allows curved canals to be prepared with a reduced chance of procedural errors such as ledges or canal transportation. The technique relies upon the narrow tip of the first rotary Shaping file following a glide path which has been previously created with hand instruments, whilst the increasingly tapered body of the file enlarges and removes dentine from the canal walls in the coronal and middle thirds of the canal. The importance of the glide path was demonstrated by Berutti *et al* (2004) and Patino *et al* (2005). Both studies showed a reduction of the incidence of file tip fracture when a pathway was created for the file to follow. The subsequent Shaping file further enlarges the deeper parts of the canal, before the Finishing files with their fixed tapers over 3mm at the tip and decreasing taper along the shank complete the preparation. The apical size is therefore increased with each subsequent file, gradually and progressively.

The second technique investigated was the reciprocating technique. This involved using the F2 Finishing file from the ProTaper sequence to complete the entire preparation (Yared 2008), following negotiation of the canal with a size 20 hand file. The same torque sensing motor was used, however, it was programmed to rotate clockwise and then anti-clockwise, with a greater clockwise than anti-clockwise rotation to allow the file to progress down the canal. Shaping files are not used in this technique, and the F2 file is used in an ‘in and out’ action, rather than the brushing action used with

Shaping files. The difference with this reciprocating technique over other reciprocating techniques is its greater rotation clockwise than anti-clockwise, and its use of a flexible nickel titanium file as opposed to stainless steel files, which have been shown to produce procedural errors such as zipping and over-preparation, especially in curved canals when used in a reciprocating handpiece (Turek and Langeland 1982) (Hülsmann and Stryga 1993).

The reciprocating technique also requires a glide path to be created prior to shaping the canal, but in this case the Finishing file used (F2) has a tip size 25 which is larger than that of the size 20 file used to create the glide path, and is therefore is not free within the canal for the entire preparation. However, the reciprocating action acts to reduce the problem of taper lock by continually reversing, which also helps reduce the build up of stress on the instrument.

Both the techniques prepare the coronal parts of the canal prior to the middle and apical thirds which is referred to as 'crown down'. This removes bacteria from their most highly concentrated area coronally (Shovelton 1964), reducing the likelihood of apical extrusion. This work demonstrated that ledges and procedural errors are more likely with the reciprocating technique than classical ProTaper when these techniques were used by dental students.

8.2 Method and Image Capture

The simulated canals used were assigned numbers randomly in a similar fashion to Spyropoulos *et al* (1987) and Sonntag *et al* (2003) to eliminate bias, as the evaluators would not be able to identify which method had been used to prepare the canals.

The simulated canals in this study were clearly marked to ensure that they could be identified and the post preparation image compared with the pre preparation image. All canals were etched with their number (Sonntag *et al* 2003), to ensure that if the number drawn on the canal was washed away, the canal could still be identified. The number also acted as a reference point (Bryant *et al* 1999) to check alignment when the pre and post preparation images were superimposed.

It was essential that the pre preparation image had a contrasting colour from the post preparation image. All canals were injected with an ink using a pipette, allowing it to be drawn along the canal by capillary action until it was filled. A number of authors have also tried to address this issue, with some using silver points in the canals to create contrast (Al Omari *et al* 1992), and others using dyes (Sonntag *et al* 2003) and ink (Berutti *et al* 2009). The ink also demonstrated that the canal was patent, as only canals where the ink penetrated the entire length of the canal were assigned a number and included in the study. Four canals were eliminated from the study due to lack of ink penetration.

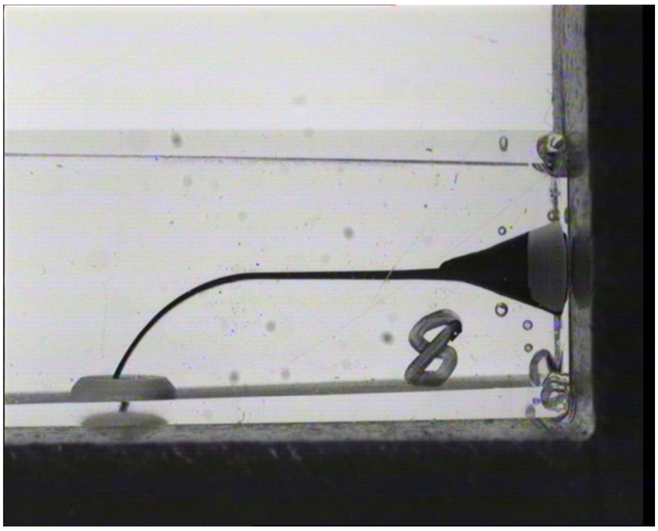

Figure 53: Simulated canal stained with ink

To capture the image, it was necessary to design a platform that would enable the simulated canal to be placed in a reproducible position each time it was photographed. Previous authors have used etched reference points on the canals (Lloyd 1997), designed custom mounts (Weine *et al* 1975), and had slots for the canals to sit in (Berutti *et al* 2009) to overcome this. In this study, an 'L shaped' metal mount was used and bonded onto a light box. This meant that as each canal was photographed, two of its sides were in contact with the mount, which prevented movement. It also allowed for some variation in the external dimensions of the simulated canals.

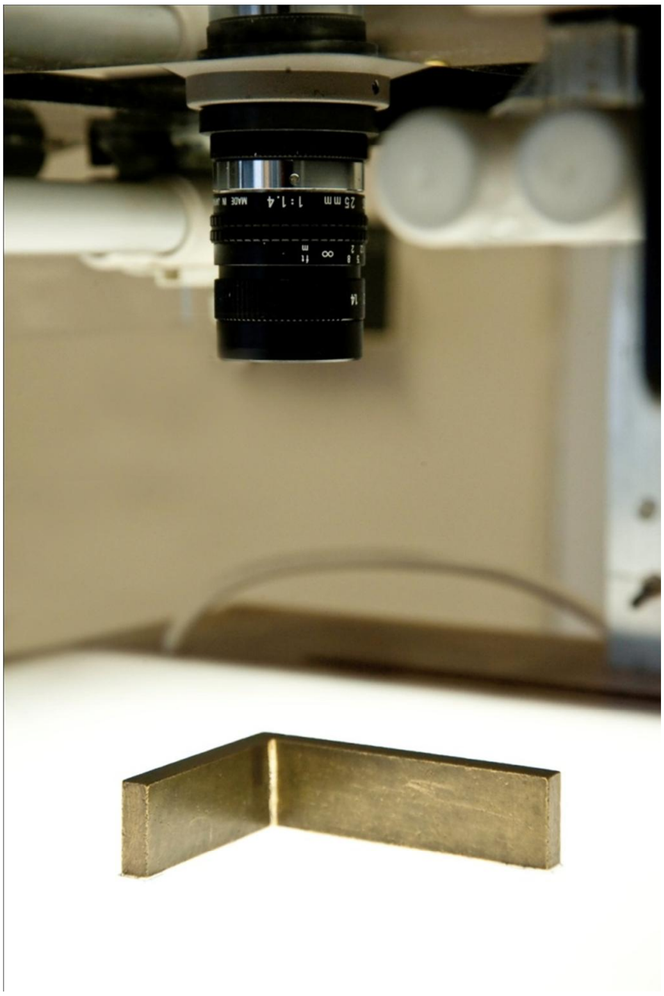

Figure 54: Platform and camera used in this study

The platform was set under a stage that retained a camera in a fixed position to prevent magnification and allow reproducibility of images. This was a similar set up to Bryant *et al* (1999), who also used a camera fixed on a stage above the canal to be photographed. The set up designed for this work also had additional lighting attached to the stage to ensure good photographic quality of the images.

8.3 Simulated Canals

Simulated resin canals (manufactured by Quality Endodontic Distributors Ltd) were used in this study as they allow standardisation of the preparation dimensions in terms of curve and length and visualisation of the preparation for analysis. They are manufactured from a resin of a hardness that gives a similar resistance to tooth tissue, but again is the same for all techniques unlike dentine which can vary in hardness. The simulated canals used in the research were 19mm long, as opposed to some available that are considerably shorter at 16mm. 19mm long canals were chosen because longer canals are more difficult to prepare (assuming the same degree of curvature is present), and therefore the likelihood of errors increases.

Lim and Webber (1985) concluded that simulated canals were a valid method for studying canal preparation, and Coleman and Svec (1997) concluded that resin simulated canals showed similar results compared to canals in extracted roots using an identical methodology. The use of simulated canals manufactured by the same company from the same batch ensured the canals were the same dimensions, and that the resin used was of the same hardness and properties. An alternative is to manufacture simulated blocks in house, forming them from silver formers which are bent to create the canal curve and then encased in a resin material (Weine *et al* 1975) (Thompson and Dummer 1997) (Bryant *et al* 1998) (Dummer *et al* 1991).

Simulated canals have the advantage over using radiographs (Javaheri and Javaheri 2007) (Backman *et al* 1992) in that it is more straightforward to compare pre and post preparation images, and they can allow three dimensional analysis. Hülsmann and Stryga (1993) concluded that,

> '*In reality the technique of radiography measures the projection of the transportation and not the real transportation, because teeth do not always display their maximum curvatures in the mesio-distal or bucco-lingual planes*'.

Another method for comparison is to inject a silicone impression material into the preparation after instrumentation to allow three dimensional analysis (Davis *et al* 1972) (Haga 1968). However, this does not allow pre and post preparation comparisons, as the tooth is generally rendered transparent through a clearing technique so the silicone can be seen through the decalcified root.

Bramante *et al* (1987) developed a sectional tooth model for the evaluation of root canal preparation pre and post instrumentation. The tooth was mounted in a muffle using dental stone. The muffle could be disassembled and the stone and tooth sectioned at the desired level and photographed pre-instrumentation. The sectioned tooth and muffle were reassembled, the canals prepared, the model disassembled and re-photographed, thereby allowing comparisons to be made. A major drawback of the technique was that it is time consuming. Deplazes *et al* (2001) also commented that,

> '...*many of the cross-sectioned specimens cannot be used because of technique-related errors. In the current study 28 canals were lost because of "ledging", which is caused when a 0.3mm-wide gap is created after sectioning the root. Consequently instruments in both test groups could not always negotiate the curved canals, and only 22 of the original 40 canals scheduled for the current study could be evaluated'*.

A much more accurate method for analysis involves the use of micro computed tomography ("mCT") Studies concluded that mCT was shown to be accurate for experimental endodontology (Plotino *et al* 2010) (Garip and Günday 2001) (Rhodes *et al* 1999). However, it is not without its problems, and Peters *et al* (2001), concluded that,

> '*Although the potential for mCT in experimental endodontology is repeatedly graded as being excellent, the reconstruction and measurement of each slice is time-consuming. For example scanning and reconstructing an upper molar requires at least three hours of operator time using the most modern systems available'*.

Gambil *et al* (1996) also mentioned in discussion that it was difficult to use the appropriate computer analysis setting as there were so many available, and that some of the changes in the sections analysed could be due to not exactly replicating the slice used, and could be attributed to distortion of the image rather than the preparation. He also noted that high resolution mCT was time consuming and expensive. However, it does remain a very accurate and useful method of studying pre and post preparation images.

8.4 The Operators

This work used inexperienced operators who had prepared less than ten canals on patients. The average experience level was seven canals, and, on a scale of 1-10 (with 10 being the most confident) the operators estimated their confidence at 6.5 before the research. The operators were given lectures, group tutorials and written protocols to enable them to complete the preparations. Gekelman *et al* (2009) found that inexperienced operators performed adequately with rotary instruments if given a structured training session, and Yared *et al* (2003) concluded that training in the technique was vital to prevent breakage and reduce deformation. Berutti *et al* (2009) found no differences in expert versus non expert preparations, and the same study (Berutti *et al* 2009) along with Sonntag *et al* (2003), Pettiette *et al* (1999), and Pettiette *et al* (2001) found that inexperienced users had less problems and performed better with nickel titanium than stainless steel files. Sonntag demonstrated that the correct preparation length was achieved significantly ($P < 0.05$) more often with rotary files than with manual files and the mean time required for manual preparation was significantly ($P < 0.001$) longer than that required for rotary preparation. Prior experience with a hand preparation technique was not reflected in an improved quality of the subsequent rotary preparation.

8.5 Motors and Set Up

For both classical ProTaper and reciprocating techniques the speed of the motors was set at 300rpm, according to the manufacturer's recommendations. Dietz *et al* (2000) found that speed was related to procedural errors, with more occurring as speed increased. Yared *et al* (2003) concluded that failures could be prevented by using ProTaper at 300rpm by a trained operator.

For the classical ProTaper technique the motor is programmed to rotate continually clockwise. The motor is torque sensing, and if a specified amount of torque required to turn the file is exceeded, then it automatically reverses to decrease stress on the file, and therefore helps prevent fracture.

The difference in the reciprocating technique was in the way the file was manipulated. It uses a greater rotation clockwise than anti-clockwise, and is timed rather than specified in degrees of rotation. This is in contrast to the balanced force technique described by Roane *et al* (1985), which used hand files, where the file is rotated clockwise to engage dentine and then anti-clockwise by a greater degree to cut. A reciprocating action has been used also with rotary handpieces, for example the 'giromatic' and 'M4'. Both of these handpieces caused the file to rotate clockwise by a specific number of degrees – 90° in the case of the Giromatic and 60° for the M4, and then reverse at speeds of between 1500rpm and 3000rpm. In the reciprocating technique using the F2 file as studied in this research, the motor that operates the handpiece is programmed to advance clockwise for 0.09 seconds, then anti-clockwise for 0.05 seconds at a fixed rotational speed of 300rpm, this cycle being constantly repeated.

8.6 Working Length and Patency

It was decided to set the working length for the preparations at 1.5mm short of the end of the simulated canal so that instrumenting long as well as short of a pre-determined working length could be interpreted. The acceptable tolerance for the working length was set at 0-1mm short of this length. It was deemed to be unacceptable to instrument longer than the working length as this would in the clinical situation result in instrumentation beyond the apex, and therefore no longer be within the confines of the root canal. Indeed, Wu *et al* (2000) concluded that, ‘*Based on biologic and clinical principles, instrumentation and obturation should not extend beyond the apical foramen’.*

The operators were also instructed to use a small size 10 file to maintain patency of the simulated canal. The file was set at 19mm to prevent build up and apical packing of debris within the canal, which may then increase the chance of procedural errors. The technique has been reported as taught in 50% of dentals schools in the USA, and is most commonly used with a size 10 file (Cailleteau 1997). There is some evidence that transportation can result with any instrumentation beyond the working length, but this is minimised if as small as possible file is used (Goldberg 2002).

8.7 Results Analysis Criteria

Schilder (1974) stated that

‘*root canal systems must be cleaned and shaped – cleaned of their organic remnants and shaped to receive a three-dimensional hermetic filling of the entire root canal space’*.

He then described a number of goals to be met for an ideal preparation. These goals and criteria were used to judge the preparations against. There are five objectives as described below (Schilder 1974).

1: Tapering funnel preparation – Criteria: Continuous taper

A continuous taper is required to cleanse the canal effectively. It permits compaction of a filling material and enables vertical forces during filling to produce a lateral component due to the tapered shape, which enhances the seal. It enhances total contact of files on canal anatomy, and enhances the effectiveness of irrigation.

2: Cross sectional diameter – Criteria: Narrower as you go apically

The canal should be narrower apically and greater coronally. The constriction apically is necessary to compact and condense the filling material against and allows condensing instruments access to the filling material which results in a good obturation. It minimises the chance of filling extrusion and maximises the chance of organic debris removal.

3: Canal preparation and the original canal – Criteria: Original anatomy maintained

Canals curve in many planes not obvious on radiographs. The greatest difficulty anatomically is apically, and when instrumenting there should be no straightening in the apical few millimetres of the canal following preparation. There should be a sense of flow to the preparation which should be apparent in the final obturated case.

4: Position of the foramen – Criteria: Foramen in its original position

The foramen should be left in its natural position. When instrumenting the canal, there is greater cutting of the canal instrument in the direction opposite to the curvature of the instrument. This results in enlargement of the foramen away from the natural curve of the canal. This transportation produces a teardrop shape for the canal exit as the apical region of the canal is straightened or possibly an outright perforation. The risk of transportation increases with inadequate access and inadequate preparation of the body of the canal. This means that space created coronally enables manipulation of the instrument apically, which in turn helps to minimise transportation.

5: Small apical opening – Criteria: Foramen as small as is practical

The foramen should be kept as small as is practical. Smaller openings simplify compaction of filling materials, but there is a need for sufficient enlargement to enable cleanliness, and anatomically teeth have varying apical sizes.

In addition to the five criteria described by Schilder, the preparations were also analysed to see if there had been coronal over-preparation, apical over-preparation or ledges created.

8.8 Instrumentation

An ideal canal preparation would meet all of the five criteria according to Schilder (1974). Unfortunately, this is not always the case, and the canal can become transported away from its original path. This produces errors, described as ledges, zips, elbows and perforations (Schäfer and Dammaschke 2006). Research has shown that there are often procedural errors when instrumenting canals, with a tendency to straighten curved canals (Pettiette *et al* 1999) (Javaheri and Javaheri 2007), produce zips and elbows (Al-Omari *et al* 1992), and widen canals apically (Park 2001) (Weine *et al* 1975). Straightening of the canal occurs due to greater removal at the apex on the outside of the curve, on the inner aspect in the middle of the curve, and the outer portion again coronally (Yang *et al* 2006) (Al-Omari *et al* 1992). The apex can appear as a teardrop shape if over extension occurs (Weine *et al* 1975) and the greater the curve, the greater the chance of instrument fatigue followed by fracture, with small changes in geometry within the canal having a considerable effect on the fatigue of instruments (Plotino *et al* 2010). Although the more flexible nickel titanium instruments have been shown to exhibit a reduced incidence of errors compared with stainless steel (Moore *et al* 2009) (Sonntag *et al* 2003), ProTaper instruments are still associated with a degree of canal transportation (Yang *et al* 2007).

The canal is first transported by the creation of a ledge. This occurs at any point short of the working length on the outer curve, where an instrument creates a ledge as it fails to smoothly pass along the length of the canal. As the file is continually trying to straighten within the canal, it will hit this ledge preferentially, making instrumentation to full length very difficult. With further filing, this can lead to the ledge becoming larger, and eventually the root can become perforated, and a communication created between the root canal and the periodontium. A zip is created apically, where the canal is over-prepared on the outer aspect of the curve, resulting in a teardrop or hourglass shape. Where there is over-preparation apically on the outside and beyond the curve, and over-preparation more coronally above the curve, this produces a narrowing often located at the point of maximum root curvature, known as an elbow.

Canals in this study in all groups were finished with an F2 Finishing file to enable comparison between the two techniques. Research has shown that larger Finishing files can produce more apical aberrations, and that as the Finishing files decrease in flexibility there is more excess removal on the inner part of the curve and a higher incidence of zipping outside of curve (Javaheri and Javaheri 2007) (Calberson *et al* 2004).

8.9 Comparison of Techniques Without Tape

The results demonstrated that students were more likely to produce a preparation that met all of Schilder's criteria if the classical ProTaper technique was used as opposed to reciprocating. However, there were not any statistically significant differences in any of the individual criteria at the 95% confidence level, but when examining the data by criterion, in general the classical ProTaper technique produced less errors and better preparations than the reciprocating technique. The results for taper are supported by the research of Peters *et al* (2003) who concluded that the ProTaper classical ProTaper technique could prepare canals

> '*without obvious procedural errors to a smooth tapered shape*'.

The reciprocating technique also produced good taper, with this occurring in 66% of preparations compared to 71% for the classical ProTaper technique. The similarity in results would be expected as both techniques are finished with the same file, and so should, if the canal patency and anatomy have been maintained, produce similar tapers especially at the apex, where the action of the Shaping file is not evident after finishing. In terms of maintenance of the anatomy, the classical ProTaper technique performed better, with 76% of preparations versus 63% for the reciprocating technique meeting the criterion. This was attributed to a number of factors. Firstly, the reciprocating technique was unlike any other they had experienced. Secondly, although both techniques had a requirement for a glide path, the size of the tip of the F2 file used in the reciprocating technique is larger than the size used to prepare the glide path, and so it would be less likely to follow this path. The importance of this path was discussed by Berutti *et al* (2004), and helps minimise procedural errors and instrument fracture. Thirdly, if the operators did not remove and clean the flutes of the instruments regularly, then this would prevent it from cutting efficiently and make the file more likely to not follow the canal anatomy. Another factor is that there may be a difference in the amount of pressure exerted on the file by the operators. Although the reciprocating technique, due to its clockwise and anti-clockwise rotation, helps prevent screwing in and so could give more of a feeling of control, there may have been more or less pressure applied, which may have influenced the trajectory of the instrument.

Most errors were recorded in the apical region of the canals. Although there was not a significant difference between the techniques, only 47% of classical ProTaper and 49% of reciprocating preparations kept the foramen as small as practical, and in terms of keeping the foramen in its original position, this criterion was met by only 58% of classical ProTaper and 54% of reciprocating preparations. These results are supported by Sonntag *et al* (2007), Schäfer and Vlassis (2004), and Aguiar and Camara (2008), who all observed apical transportation with ProTaper files. All files have a tendency to straighten within the root canal regardless of the material used. Schäfer and Dammaschke (2006) stated that during instrumentation,

> '*Owing to the restoring forces, an uneven force distribution of the cutting edges of the instrument in certain contact areas along the root canal wall results, leading to an asymmetrical dentin removal. In particular, the cutting edges are pressed against the outer side of the curved canal (convexity) in the apical third and against the inner side at the middle or coronal thirds (concavity). As a result, apical canal areas tend to be over-prepared toward the convexity of the canal, whereas more coronally greater amounts of dentin will be*

removed at the concavity, leading to canal transportation or straightening of varying degrees.'

This straightening problem was also described by Peters (2004), Hülsmann (2005) and Bergmans *et al* (2001), and as in the case of this research, the main areas where this is observed are apically on the outside of the curve, on the inside of the curve in the mid root area, and coronally again on the outside of the curve. The apex becomes enlarged or transported when either an instrument passes beyond the working length, is allowed to dwell at the working length, or where a ledge has been created and the operator pushes to get the Finishing file to the working length.

Coronally, there were very few instances of over-preparation, whether the canals were masked or not, or regardless of the technique used.

8.10 Comparison of Techniques With Tape Used

There were a number of statistically significant differences between classical ProTaper and reciprocating techniques where tape was used to mask the simulated canals. Masking tape was applied to see if there were any differences compared to the first part of the research which was completed with no tape, and to better simulate the situation in the mouth, where the operator cannot see what is happening to the instrument, and must rely on pre treatment images and tactile feedback. In every instance of statistical significance, it was the classical ProTaper technique that produced less procedural errors, and was therefore more likely to produce a preparation that met all Schilder's criteria (Schilder 1974). The criteria that produced significant differences at the 95% confidence level were in maintaining the original anatomy, becoming narrower as the preparation progressed apically, and in the incidence of ledges. There were statistical differences in producing a continuous taper and keeping the foramen as small as practical, but these were at the statistically weaker 90% confidence level.

The differences could be attributed to the classical ProTaper technique enabling progressive creation of shape along the canal length. Both techniques ensured instrumentation to a size 20 hand file, but with the classical ProTaper technique, the use of the Shaping files to create some coronal shape before achieving working length reduced the load on the file, and enabled it to follow the canal path more easily as the file is not restricted in the coronal and mid root portions which can prevent advancement apically. The establishment of progressive shape within the canal and an effective glide path, as previously explained, minimises fracture risk (Berutti *et al* 2004) and stress on subsequent files, which may help explain the reduced incidence of ledging with the classical ProTaper technique where the canal is gradually enlarged with four Shaping and then two Finishing ProTaper files. When the F2 file is used straight after the size 20 glide path file, as in the reciprocating technique, then the tip of the F2 produces enlargement over a greater length of the canal compared to the classical ProTaper technique. This is due to the taper of the instruments used. In the case of the reciprocating technique, the instrument that enlarges the canal prior to the F2 file is an 02 tapered size 20 file. The taper of the instrument being 02 results in the diameter of the file increasing by 0.02mm every millimetre back from the tip. In reality this results in the file being 0.025mm in diameter 2.5mm back from the tip. This is relevant considering that the F2 is 0.025mm at the tip, and so from 2.5mm from the apex of the preparation, the established glide path is narrower than the F2 file tip. With the classical ProTaper technique, the previous file that enlarges the canal is an F1 Finishing file. This has a tip size of 20 and an 07 taper. This instrument is 0.25mm in diameter under 1mm from the tip, and so results in the subsequent F2 file tip engaging over a shorter length because of the previous enlargement of the canal with the F1.

If the canal has been ledged, then this widening on the outside wall means the canal does not become narrower as it goes apically. As it straightens, the file will continue to follow the outside wall of the curve. The reciprocating action has a different feel to rotary as the instruments are not pulled in to the same degree. Increased pressure applied to the file by the operator in order to increase file advancement may, in fact, result in worsening of a ledge. It is therefore very important that operators remove instruments and check for canal patency with a small file when apical advancement of instruments stops, to minimise such problems. It is also important that the file is regularly removed to clean the file and remove debris from the flutes, as if the flutes are loaded with debris, the file will no longer advance, and the operator may therefore apply more pressure to keep the file advancing.

8.11 Analysis of Results by Location Within the Canal

8.11.1 *Coronal*

In general there was little over-preparation coronally, especially where the reciprocating technique was used regardless of whether or not the preparations were masked. With classical ProTaper, the Shaping files are used in a brushing action to shape the coronal part of the canal. This is not the case for the reciprocating technique, where only a Finishing file is used without brushing. There was one instance of coronal over-preparation with the reciprocating technique, which was a result of the student leaning on the file coronally. This resulted in a preparation where the canal pathway was straightened by the file away from its central axis. This is shown below.

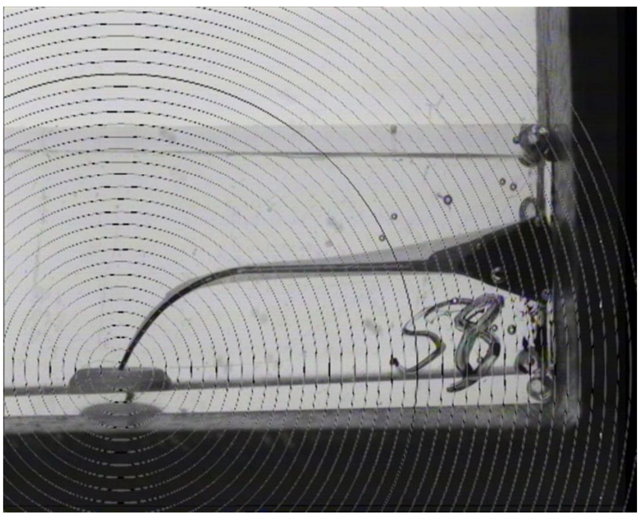

Figure 55: Coronal over-preparation with the reciprocating technique

The same problem also occurred with classical ProTaper with the operator leaning with the file rather than brushing, but with a more destructive result. This may be due to this technique using more files, which would mean that any error in manipulation is magnified as it is repeated for every file. It is also probably more over-prepared as with classical ProTaper the file continually rotates, rather than rotating clockwise and anti-clockwise as is the case with the reciprocating technique, and so for the same length of time of preparation, the file is cutting for a longer period. An example is shown below.

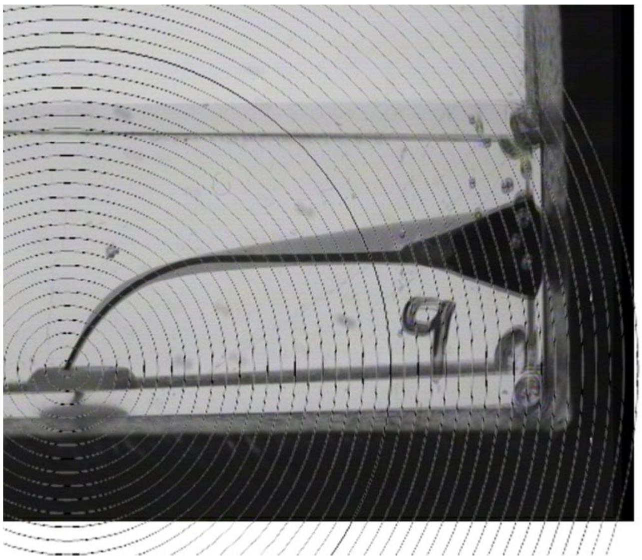

Figure 56: Coronal over-preparation with classical ProTaper due to the student leaning with the Shaping file rather than using it in a brushing action

The other way in which over-preparation occurred was as a result of over-use of the Shaping files, where a combination of brushing and leaning with the file produced a very wide distorted preparation. Brushing is intended to be done only with Shaping files, and is a way of differentially removing dentine preferentially from one side of the canal. It is done by manipulating the handpiece to allow the middle part of the file to prepare the canal walls as it is withdrawn from the canal.

Leaning on the file is done as the operator angles the handpiece in the intended direction, but does not guide the middle part of the file.

Below is an example of over brushing and leaning with the Shaping file that has produced a very over-prepared result, and was probably due to errors in manipulation of the instruments.

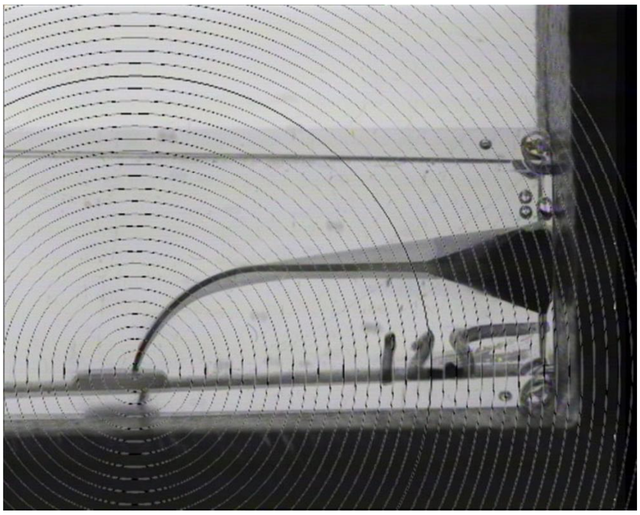

Figure 57: Over brushing and leaning with the Shaping file

8.11.2 ***Mid Root***

For all techniques the greatest amount of canal enlargement was at 5mm from the apex on the inside of the curve (see Figure 58 overleaf). There was a slightly greater removal when classical ProTaper was used, and where tape obscured the canal. The greater removal could be due to the fact that for the classical ProTaper technique, two Shaping files and two Finishing files are passed along the canal, whereas with the reciprocating technique, there is only one. The results for the time taken also demonstrate that the reciprocating technique takes a shorter amount of time than the classical ProTaper technique, which results in the canal not being exposed to the instruments for as long, which again may explain the reduced removal of material. This is also a potential reason for the no tape groups removing slightly less but not statistically significant amounts of material, as the times taken for these groups were less than the groups with no tape used.

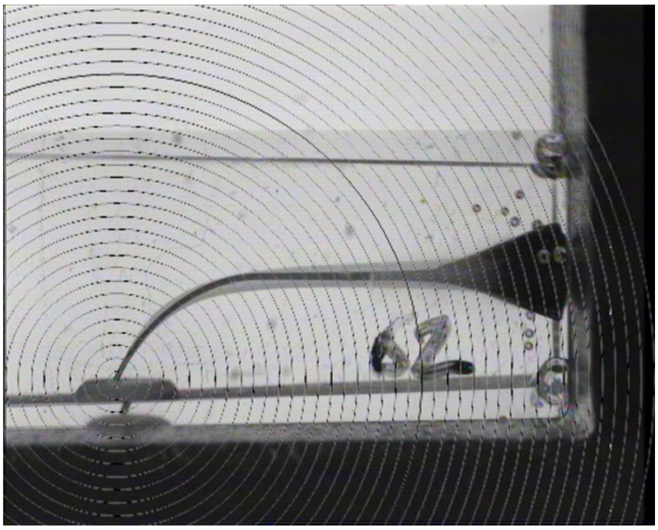

Figure 58: Increased removal on the inside of the canal 5mm from the specified working length

At 7mm from the apex, the differences were between the tape used and no tape groups rather than the techniques. The tape used groups had slightly greater removal on the inside of the curve than when the operator could see the preparations. This could be due to the increased time taken, or that the files were allowed to linger at length with this group, which would result in increased removal as the file attempts to straighten within the canal.

8.11.3 *Apical*

The reciprocating technique results generally demonstrated a lack of control of the apical portion. There were numerous ledges and instances where the foramen was not as small as practical, and preparations not narrower as they progressed apically. This may have occurred due to the file not following the canal as well as in classical ProTaper, and so creating ledges. If the file was also allowed to dwell in one position whilst not advancing apically, it may remove additional material from the outer canal wall thereby creating a ledge. This may have occurred at any location along the canal, and could account for the ledges which were recorded within 1mm of the specified working length, and therefore probably where the operator intended the preparation to finish. An example is shown below.

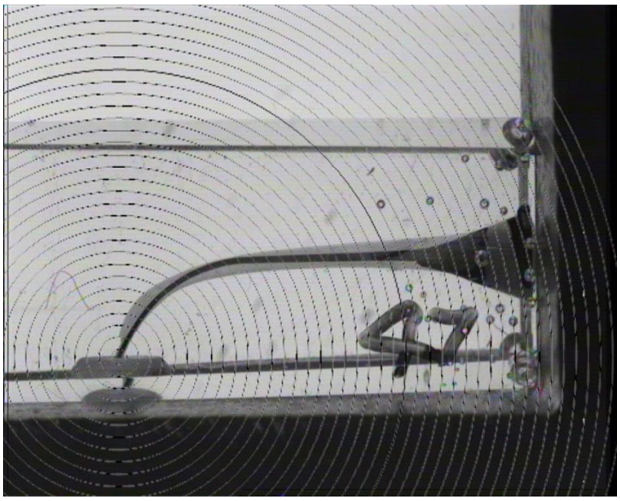

Figure 59: Apical over-preparation with classical ProTaper technique with tape used due to lingering at the working length with the file

The number of ledges in the apical third of the preparation with the reciprocating technique where tape masked the canals was statistically significant ($p<0.05$). The position of these ledges was measured to examine any correlations. The reciprocating technique produced more ledges in the area from 1mm to the specified working length compared with classical ProTaper, but this was in the accepted tolerance of working length and may be considered to be the finishing point of the preparation. It may also be that the evaluators could see the end point more clearly when only the F2 has been used as is the case with the reciprocating technique, whereas with the classical ProTaper technique the S1, S2, F1 and F2 probably did not all go to the same length, as the curved canal length changes as it straightens. This would produce a blend of smaller ledges which may be less visible to the evaluators. An example of a ledge created within 1mm of the specified working length produced using the Classical ProTaper technique with tape used is shown below.

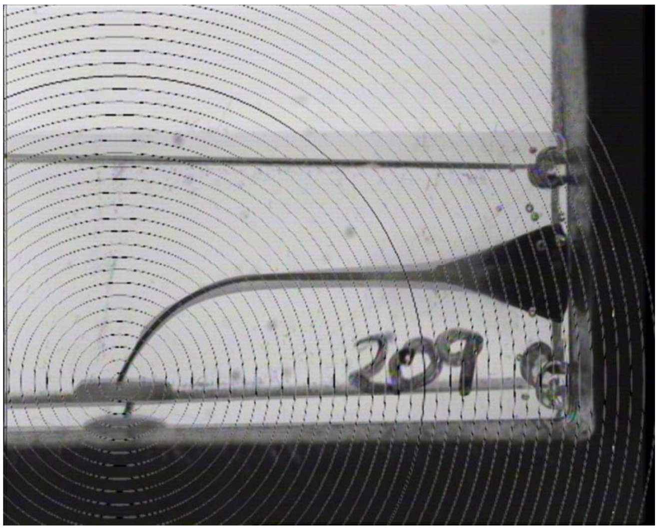

Figure 60: Classical ProTaper preparation with tape demonstrating a ledge within 1mm of the specified working length

The reciprocating technique also produced a concentration of ledges at the 2mm – 2.5mm distance from the specified working length (see Figure 61 overleaf). When viewing the blocks all these ledges always appeared on the outside of the curve. Classical ProTaper produced fewer ledges, and those that occurred were mostly within 1mm of the specified working length of the preparation. This may have been where the operator intended to finish the preparation, and is within the tolerance of accepted working length. With the reciprocating technique, the ledges at 2mm - 2.5mm from the apex were in the location that the F2 file did not have an established glide path, due to the narrower taper of the previous file to negotiate the canal, as described earlier (Section 8.10).

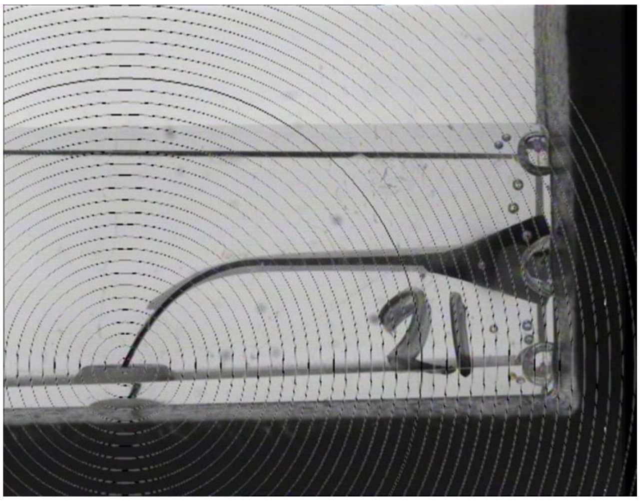

Figure 61: Ledge formation more than 1mm from the specified working length using the reciprocating technique with no tape used

Ledges may prevent the operator achieving the pre-determined working length. Due to the shape memory of nickel titanium, when a ledge is created the file will always hit the ledge as it follows the outside of the curve as it advances apically. This changes the anatomy and prevents the original anatomy from being maintained. The ledge is then generally increased in magnitude as operators continue to try to prepare to what they consider to be the original canal working length, without realising the canal has been diverted. With the reciprocating technique it appeared that this was more likely to occur 0.5mm and 2.5mm from the apex.

In the ideal preparation, the shape tapers from the coronal opening to the apex continuously and has its narrowest point apically at the pre-determined working length. With the reciprocating technique and the incidence of ledges, this meant that the apex has often been transported away from the original position and so the canal was no longer negotiable within its original shape. In most cases the ledge is created at a site distant from the apex and is enlarged as the file attempts to straighten the canal. This results in a wide apex and so does not have the foramen as small as practical and is not narrower as it goes apically. The ledge may have been created as the operator was aware that the preparation was nearly complete, and may have pushed apically with greater pressure a file that was loaded with debris, rather than removing and reintroducing it. It could also have occurred because the rotary file screws into the canal and takes the operator past the intended working length.

Below is an example of loss of anatomy apically and ledge formation. This may have resulted from lingering first to produce the ledge, then pushing to try to get to the specified working length.

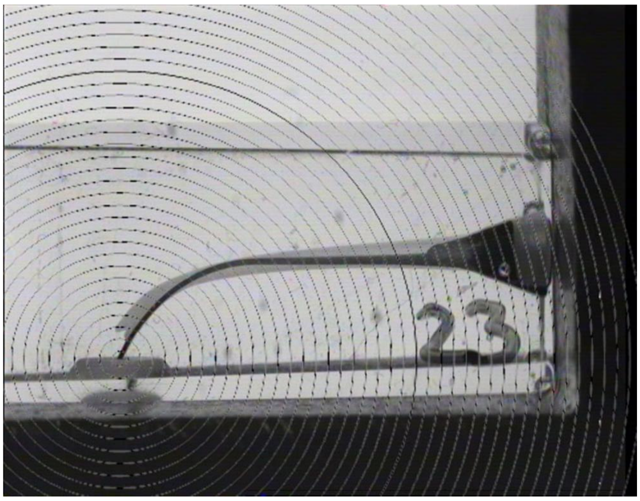

Figure 62: Loss of anatomy and not becoming narrower as you go apical and ledge formation with classical ProTaper technique

The differing debris removal capabilities of the two techniques could also contribute to the difference in the number of ledges. With the classical ProTaper technique, the use of the Shaping files, and the continual clockwise rotation of the files removes more debris as the canal is gradually enlarged. This resulted in a clear path for the Finishing files that are therefore less likely to cause a ledge as they more easily pass down the canal. Debris has also been proposed by Alapati *et al* (2004) as a causative factor in instrument failure, as dentinal chips become embedded in the flutes of root canal instruments and therefore prevent efficient cutting and further debris removal.

8.12 Tape Comparisons

Using the reciprocating technique, the students performed no differently ($p>0.05$ for all criteria) whether tape was used or not, hence whether they could see the preparation made no difference to the outcome. Using the classical ProTaper technique the students performed less well if they could see the preparation ($p=0.0153$ foramen as small as practical). This was thought to be as a result of the students sticking to a strict regime and protocol and being careful to work to the prescribed length when they could not see it, as opposed to instrumenting to what they estimated to be the working length visually. If they could not see the preparation, the students were also more likely to be more careful and tentative. They would concentrate on brushing in the correct dimension with the Shaping files, rather than concentrating on the end or apex of the preparation.

8.13 Timing Comparisons

The amount of time taken to prepare the canals was assessed. The quicker technique overall was the reciprocating technique, although not at a statistically significant level. This is because only one rotary file is used, compared to four with the classical ProTaper technique. It was not much faster though, probably because the technique was new to the students and had a different feel.

As expected, both techniques were completed faster if there was no tape used as the operators were more confident, and could see what they were trying to achieve. This also could account for the improved results achieved by the obscured groups, and the apex not being kept as small as practical ($p=0.0153$) when the students could see the preparation, because the preparations were not as rushed and files pushed to get them to the length specified.

8.14 General Observations

Results for the reciprocating technique showed a reduced amount of canal material removal compared with classical ProTaper technique, indicating that it was the more conservative technique. This is probably because Shaping files are not used. However, the reciprocating technique did produce a well centred preparation, with more removal on the outside of the curve at 3mm and less on the inside at 5mm. An example is shown below.

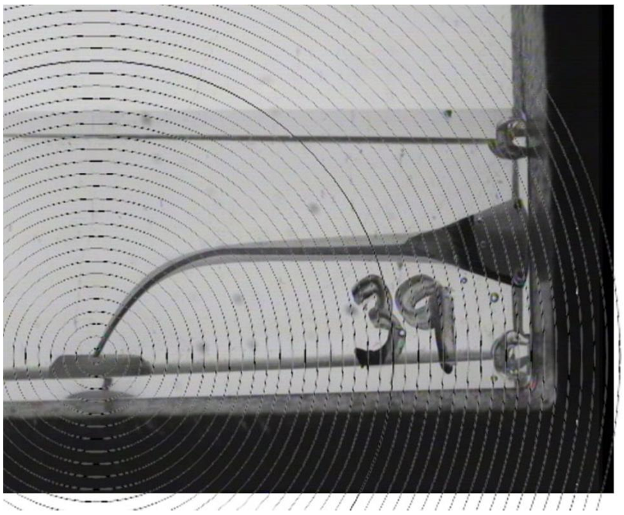

Figure 63: Well centred preparation with the reciprocating technique

However, caution is advised with these results as the number of ledges was greater with the reciprocating technique, especially at the 2.5mm region which result in greater removal on the outside of the curve, and subsequently reduce the amount on the inside of the curve as the file has already straightened to create the ledge.

8.15 File Straightening

The measurements for the amount of material removed at four locations along the canal demonstrate the straightening tendency of the file as it prepares the canal. Nickel titanium files have great flexibility and shape memory. This means that the file will prepare curved canals, but does straighten within the canal as it prepares (Vaudt *et al* 2009) (Calberson *et al* 2004). This is demonstrated by the greatest removal in the blocks on the outside of the curve at 1mm and 3mm, on the inside at 5mm and again on the outside at 7mm. This may be due to the fact that the curvature of the block was too great for the F2, and that this file should not therefore be taken to length, but stepped back if the canal possesses a curvature of this magnitude. The increased removal at 1mm and 3mm could also be due to the file straightening if the Finishing files are allowed to dwell at their working length rather than remove them as soon as the length is achieved.

Figure 64, below, demonstrates the effects of the file straightening within the canal. The canal has been prepared long and demonstrates the damage to the canal anatomy that can occur with loss of control of length of the preparation.

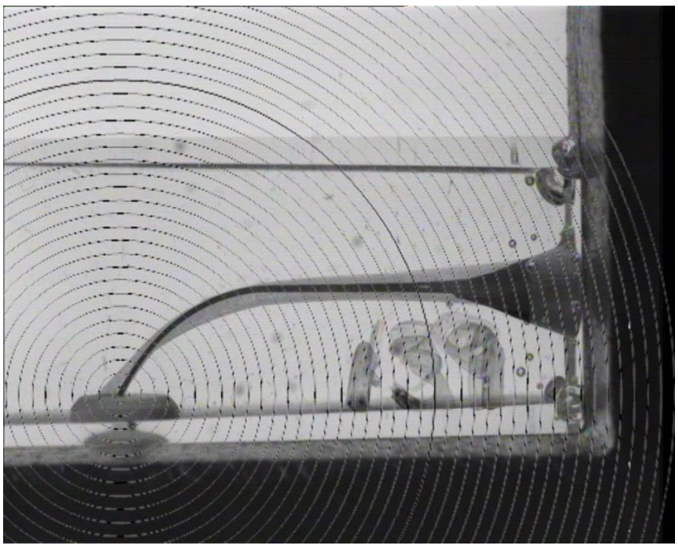

Figure 64: Straightening of the file from the outside of the curve coronally to the inside in the mid third of the root and again on the outside apically as the file is allowed to dwell in the canal

8.16 File Fracture

ProTaper has a triangular cross section to decrease the contact with the root canal wall and so minimise the screwing in effect. The shape ensures a high degree of flexibility, but also strength and therefore helps resistance to fracture. The Shaping files have a different cross section to the Finishing files, with the Finishing files having a concave rather than convex cross section to increase their flexibility. ProTaper files will ‘spring back’ to their original shape when stress is removed, but will distort or break if stressed to a greater level than that which causes permanent deformation. The cause of fracture is often too much load applied by the operator, which in turn increases the torque on the instrument. The file fractures as the load imparted by the operator exceeds the resistance of the file. There are a number of possible causes of fracture. The first is fracture of the tip of the instrument. With classical ProTaper, the Shaping files with their variable taper are free at the tip as they have a smaller tip diameter than that of the file used to create the glide path. They therefore prepare the canal wall where they have more strength, in a shorter length of file compared to the reciprocating technique where there are no Shaping files, and the tip of the instrument is not smaller than its glide path, and so is not free. A second cause of fracture is due to taper lock. This occurs where the file rotates and becomes locked into the canal wall along its length. As the motor continues to attempt to turn the file, it fractures, as the amount of torque produced exceeds the resistance of the metal it is manufactured from. This should, in theory, be less of a problem for the reciprocating technique, as the file is not continually rotating. The clockwise and anti-clockwise action prevents the accumulation of stress, as any taper lock is negated by the file reversing after it advances. Another suggestion as to the cause of failure of instruments, as described earlier, is by debris build up in the flutes (Alapati *et al* 2004). In this research project, the file that fractured was when reciprocating technique was used. This could also be attributed to the operator imparting too much pressure on the file as it was a different feel and not something they had experienced before.

Figure 65, below, is an example of a reciprocating preparation with anatomy not maintained. This was due to file fracture in the apical region, followed by its reintroduction without the operator realising it had fractured. The fracture removed the safe end of the file resulting in a sharp cutting tip which will not negotiate the curve.

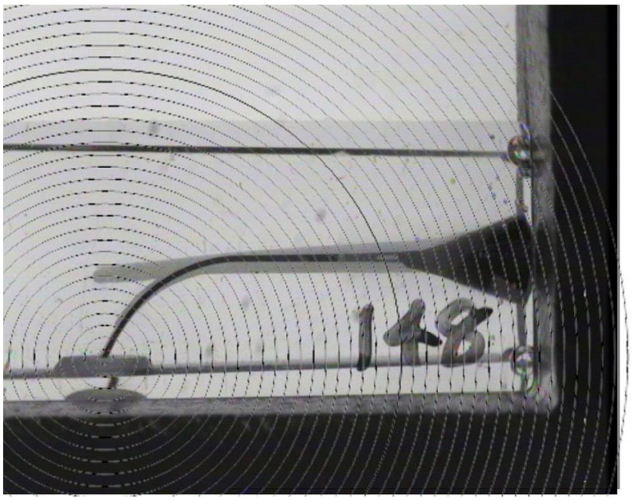

Figure 65: Reciprocating technique preparation with anatomy not maintained

8.17 Student Feedback

In the questionnaires, most students named the reciprocating technique as the technique that they preferred. It was not due to the quality of the results, a factor only mentioned in three comments out of all the questionnaires. The reasons for their preference were due to its speed of preparation and simplicity of technique.

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9 Conclusion

This research demonstrated that the classical ProTaper technique of four files was more likely to produce a preparation meeting all of Shilder's criteria for ideal mechanical preparation of root canals than the reciprocating technique using one file.

Where the simulated canals were not masked, so the operators could see the canal they were preparing, this produced no statistically significant differences at the 95% confidence level between the techniques for any of the research criteria. However, in general the classical ProTaper technique produced preparations that were more likely to meet Schilder's criteria than the reciprocating technique. Most errors that occurred using both techniques were in the apical region, with very few errors for either occurring in the coronal and middle thirds of the canal.

Where the simulated canals were masked with tape, there were a number of statistically significant differences between the techniques. In every instance, it was the classical ProTaper technique that produced the better preparations, based on Schilder's criteria. The statistically significant differences occurred in maintaining the original anatomy of the canal, the canal becoming narrower as it went apically, and in the incidence of ledges.

Both techniques had a requirement for a glide path to be created using a size 20, 02 tapered stainless steel hand file. With classical ProTaper, this was created using Shaping files to create coronal shape before achieving the specified working length. This helps to minimise the load on subsequent files, and enables them to better follow the canal path. The reciprocating technique uses only one file to complete the entire preparation. This has benefits in terms of simplicity of technique and obvious benefits in cost saving due to root canal instruments all being single use only. The disadvantage is that there are no Shaping files to create coronal shape prior to achieving working length. The F2 instrument that is used with the reciprocating technique has a larger tip size and taper than that used to create the glide path, and so produces enlargement over a greater length of the canal compared to the classical technique. The point at which the F2 file has a greater diameter than that of the glide path is 2.5mm from the specified working length due to the taper of the instruments, and it is in this region that a collection of ledges occurred with the reciprocating technique, whereas this did not happen for the classical ProTaper technique.

In terms of comparing where tape was used to mask the canals and where it was not, it was more likely that a preparation would meet all of Shilder's criteria where tape masked the canals. However, there were no statistically significant differences between the groups when the reciprocating technique was used.

With the classical ProTaper technique, where tape masked the canals, there was a statistically significant difference in keeping the foramen as small as is practical. This criterion was met on more occasions when tape masked the preparations and the operator could not see the canal. This was attributed to the operators following the technique protocol more precisely when they could not rely on visualisation of the canal for the interpretation of the specified working length. The clinical relevance of this is that the masking of the canals helps to better replicate the conditions in the mouth where the operator must rely more on tactile sense and feedback from the instruments rather than what they can see.

The fact that there were significant differences between the results using masked and unmasked canals raises concerns over the degree of clinical relevance research may have where unmasked simulated canals are used. It also demonstrates the need to research further the differences between the classical ProTaper and reciprocating techniques in extracted teeth, where there is more clinical relevance and the findings of this research can be supported.

Overall, it was demonstrated that inexperienced operators produce better and more consistent preparations when using the classical ProTaper technique with four files as opposed to the reciprocating technique with one.

Appendix A- Classical ProTaper Protocol

Classical ProTaper Technique Protocol

Introduction:

ProTaper is a variable taper nickel titanium system. The taper of the instrument varies from the tip to the end of the cutting flutes. This enables shaping which respects the original anatomy of the canal and irrigant access further down the root canal system. The files have a convex triangular cross section and a varying helical angle and pitch. They are designed to maximise efficiency and flexibility but minimise torsional stresses because of this flute design.

There are 3 Shaping files:

SX/S1/S2

There are 5 Finishing files:

F1/F2/F3/F4/F5

There are also other files available in the system including retreatment files. There are matched paper points, gutta percha points and Thermafil obturators to enable well adapted obturation to the prep sizes.

The Shaping files have increasing taper along their length rather than a fixed increasing taper. This has the advantage that as long as the canal has been explored appropriately – often to at least a size 20 hand file - the tip will remain free of the canal walls, allowing the body of the instrument to be effective and shape the canal without fear of the file binding in the apical region, thus minimising the risk of tip separation.

The SX file is an access instrument that is of benefit in shorter canals, and where access is needed to be improved after initial access and identification of the canals. This is vital with this instrument as the tip must be kept free to prevent separation.

Finishing files have an increasing taper at the tip to enable shaping of the apical area and have standard tip sizes.

Shaping files:

S1: Taper 2-11% with 14mm of cutting flutes. Tip size 17.

S2: Taper 4-11.5% with 14mm of cutting flutes. Tip size 20.

SX: 9 compacted tapers with 9mm of cutting flutes.

Finishing files:

F1: Taper at the tip 7% - Tip size 20

F2: Taper at the tip 8% - Tip size 25

F3: Taper at the tip 9% - Tip size 30

F4: Taper at the tip 6% - Tip size 35

F5: Taper at the tip 5% - Tip size 40

Technique:

Your working length of the artificial canal will be 17.5mm in these blocks.

During the procedure, you must maintain patency with a size 10 file set 1.5mm longer than the working length (19mm).

You must irrigate with copious amounts of irrigant and recapitulate regularly.

Fill in the first part of the questionnaire.

Coronal Preparation:

- Using a plastic endo block, explore the canal with hand files.
- Use hand files sizes 10/15/20 with a precurved tip to the instrument.
- Gently beginning with the size 10.
- Work to where the file will go without pressure using a watch winding motion.
- Transfer this length to the 15 and 20.
- Do the same with these files.
- Transfer the length you got with the size 20 to the S1 rotary instrument.
- Ensure the speed of the motor is set to 300 RPM and the torque to infinity.
- Introduce the rotating Shaping file into the block and work to the length described.
- You must use a brushing action on the outstroke brushing away from the curve.
- Remove the file every 5 times you advance it to clean it and remove any debris.
- Clean it with a moist gauze.
- When you have reached this length, move back to your hand files.

- Using the 10/15/20 files in the same way as before, obtain your working length.
- This will be 17.5mm in these blocks.
- Start with the size 10 hand file again.
- Use a watch winding motion in the presence of irrigant.
- Then do the same with the size 15 and then 20.
- Maintain patency of the block with the size 10 instrument .
- Regularly irrigate with water and recapitulate with hand files.

At this stage you should be able to get to your working length with the size 20 hand file.

Then move to the rotary instruments.

- Confirm your working length with the size 20 hand file.
- Using S1 and brushing with the instrument away from the curve on its way out of the canal take it to your working length.
- Regularly irrigate with water and recapitulate with hand files.
- Take the S2 instrument to length in the same way as with S1.
- Regularly irrigate with water and recapitulate with hand files.

Apical Preparation:

- Then use the Finishing files.
- Set the working length using the rubber stops to 17.5mm.
- First check to see if sufficient shaping has been completed with the Shaping files by placing the F1 Finishing file into the canal until it will not freely advance any further without rotation. If the distance from the rubber stop to the coronal edge of the simulated canal is greater than 2mm, then more preparation is needed with the S2 Shaping file as above. If the distance is 2mm or less, then proceed as below.
- Take F1 to your working length in an in and out picking motion.
- Do not allow it to dwell in the canal.
- Irrigate and check patency.
- Take F2 to the same length in the same way.
- Irrigate and recapitulate.

Record your finishing time.

Fill in the questionnaire.

Appendix B – Reciprocating Technique Protocol

Reciprocating Technique Protocol

Introduction:

ProTaper is a variable taper nickel titanium system. The taper of the instrument varies from the tip to the end of the cutting flutes. This enables shaping which respects the original anatomy of the canal and irrigant access further down the root canal system. The files have a convex triangular cross section and a varying helical angle and pitch. They are designed to maximise efficiency and flexibility but minimise torsional stresses because of this flute design.

There are 3 Shaping files:

SX/S1/S2

There are 5 Finishing files:

F1/F2/F3/F4/F5

There are also other files available in the system including retreatment files. There are matched paper points, gutta percha points and Thermafil obturators to enable well adapted obturation to the prep sizes.

The Shaping files have increasing taper along their length rather than a fixed increasing taper. This has the advantage that as long as the canal has been explored appropriately – often to at least a size 20 hand file - the tip will remain free of the canal walls, allowing the body of the instrument to be effective and shape the canal without fear of the file binding in the apical region, thus minimising the risk of tip separation.

The SX file is an access instrument that is of benefit in shorter canals, and where access is needed to be improved after initial access and identification of the canals. This is vital with this instrument as the tip must be kept free to prevent separation.

Finishing files have an increasing taper at the tip to enable shaping of the apical area and have standard tip sizes.

Shaping files:

S1: Taper 2-11% with 14mm of cutting flutes. Tip size 17.

S2: Taper 4-11.5% with 14mm of cutting flutes. Tip size 20.

SX: 9 compacted tapers with 9mm of cutting flutes.

Finishing files:

F1: Taper at the tip 7% - Tip size 20

F2: Taper at the tip 8% - Tip size 25

F3: Taper at the tip 9% - Tip size 30

F4: Taper at the tip 6% - Tip size 35

F5: Taper at the tip 5% - Tip size 40

Technique:

Your working length of the artificial canal will be 17.5mm in these blocks.

During the procedure, you must maintain patency with a size 10 file set 1.5mm longer than the working length (19mm).

You must irrigate with copious amounts of irrigant and recapitulate regularly.

Fill in the first part of the questionnaire.

Negotiation

- Using a plastic endo block, explore the canal with hand files.
- Use hand files sizes 10/15/20 with a precurved tip to the instrument.
- Gently beginning with the size 10.
- Work to where the file will go without pressure using a watch winding motion.
- Transfer this length to the 15 and 20.
- Do the same with these files.

- Using the size 10, 15 and 20 hand files sequentially and using a watch winding motion with abundant irrigation and recapitulation work until you can attain your working length with the size 20 file.
- This will be 17.5mm in these blocks.
- Maintain patency of the block with the size 10 instrument.
- Regularly irrigate with water and recapitulate with hand files.

At this stage you should be able to get to your working length with the size 20 hand file.

Confirm your working length with the size 20 hand file.

Preparation

- Then move to the F2 rotary instrument.
- For this technique ensure the motor is set for reciprocating. Ask a staff member to confirm this.
- The speed must be set at 300 RPM.
- Set the working length to 17.5mm using the rubber stop.
- Work to length using the F2 instrument only.
- Use a gentle picking motion.
- Clean the instrument every 5 times you advance the file.
- Regularly remove the file and clean the flutes with moist gauze.
- Irrigate and recapitulate the canal.

Record your finishing time.

Fill in the rest of the questionnaire.

Appendix C – Questionnaire

Questionnaire For Endodontic Techniques

About You:

Are you male or female?

Which year are you in?

How confident are you about endodontics?

(Score 1-10. 1=Very unconfident/10=Extremely confident)

How many canals have you treated on patients?

About The Technique:

Which technique did you use?

What is your start time?

What is your finishing time?

How easy was the protocol to follow?

(Score 1-10.1=Impossible/10=Very easy)

Did you break any instruments? If so which ones?

(Y/N-Explain which ones were broken)

About The Information and Instructions:

Did you receive enough information to complete the techniques?

(Rate 1-10.1=Not enough/10=Plenty)

How easy were the instructions to follow?

(Score 1-10.1=Not at all easy/10=Very easy)

Assessment:

How confident do you now feel with the technique?

Score 1-10.1=Unconfident/10=Very confident)

After Completing All Techniques:

Which technique did you like the most?

(Classical ProTaper/Reciprocating)

Why?

Thank you