UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

A Micro-Computed Tomographic Evaluation of Curved Maxillary Molar Root Canals After Using Different Root Canal Instrumentation Techniques

PEET J VAN DER VYVER

Thesis submitted in the fulfilment of the requirement of the degree

Doctor of Philosophy (Ph.D.)

Department of Odontology, School of Dentistry, Faculty of Health Sciences
University of Pretoria, Pretoria, South Africa

Supervisor: Professor FA de Wet (DSc)

December 2017

Learning is a treasure
that will follow its owner
everywhere

-Chinese Proverb

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

It is with the highest appreciation and gratitude that the author would like to thank:

Prof FA de Wet – supervisor, Department of Odontology, University of Pretoria, Pretoria, South Africa for his guidance and mentorship the last 22 years of my career.

Dr Farzana Paleker for her valuable assistance and unrelenting support.

Prof HS Schoeman, Statistician/Owner of Clinstat CC, Pretoria.

Ms Clarissa Sutherland, for her assistance with the micro-CT analysis.

Ms Barbara English for her assistance in language editing.

Mr Jacobus Hoffman, technician at NECSA for his assistance with the micro-CT Imaging.

NECSA, for the use of the facility.

My beautiful wife, **Leigh Spamer,** for her continual support and encouragement.

My children, **Jaco**, **Anzel** and **Canna –** my daily inspiration and motivation.

My staff, **Ms Debbie Malan** and **Ms Lindi Peterson** for all their hard work towards this project.

God Almighty for the health and strength to complete this Thesis and Degree.

DECLARATION

I, Petrus Jacobus (Peet) van der Vyver, declare that this dissertation entitled, **"A Micro-Computed Tomographic Evaluation of Curved Maxillary Molar Root Canals After Using Different Root Canal Instrumentation Techniques"**, I herewith submit to the University of Pretoria in fulfilment of the requirements for the degree Degree Doctor Philosophy (Doctor of Philosophy) is my own original work, and has never been submitted for any academic award to any other institution of higher learning.

______________________________ 07 December, 2017

Petrus Jacobus van der Vyver **DATE**

SUMMARY

Preservation of the original anatomical shape following instrumentation of root canals is essential for endodontic success. Procedural errors created during glide path enlargement might be exacerbated or initiated during subsequent shaping.

The aims of this study were to: (1) compare canal centering ability and transportation of pre-curved Senseus K-FlexoFiles (stainless steel), ProGlider file (M-Wire) and One G file(NiTi alloy) after glide path enlargement in curved root canals micro-computed tomography (micro-CT) scanning; (2) compare canal centering ability and transportation of OneShape (NiTi alloy), ProTaper NEXT (M-Wire alloy) and WaveOne Gold (Gold wire) instrumentation techniques in the same canals; (3) compare the change in root canal volume between uninstrumented canals, canals after glide path preparation, and canals after root canal preparation.

One hundred and thirty-five curved mesio-buccal root canals of human maxillary molars were randomly divided into three groups. These groups were (1) glide path enlarged using pre-curved size 10, 15 and 20 stainless steel Senseus K-FlexoFiles (n=45); (2) manual glide path enlargement with a size 10 K-File followed by One G (n=45); and (3) manual glide path enlargement with a size 10 K-File followed by the ProGlider (n=45). Micro-CT was used to scan teeth before and after glide path preparation.

Each glide path specimen group was randomly assigned to three equal groups (n=15) resulting in nine glide path/shaping groups of fifteen canals each: Group 1 (K-FlexoFile + OneShape)(K/OS); Group 2 (K-FlexoFile + ProTaper NEXT)(K/PTN); Group 3 (K-FlexoFile + WaveOne Gold)(K/WOG); Group 4 (One G + OneShape)(OG/OS); Group 5 (One G + ProTaper NEXT)(OG/PTN); Group 6 (One G + WaveOne Gold)(OG/WOG); Group 7 (ProGlider + OneShape)(PG/OS); Group 8 (ProGlider + ProTaper

NEXT)(PG/PTN); and Group 9 (ProGlider + WaveOne Gold)(PG/WOG). After canal preparation with the shaping instruments, all the specimens were scanned again by means of micro-CT.

The three-dimensional images obtained before instrumentation, after glide path preparation, and again after final canal preparation were reconstructed and interpreted. Centering ratio values, canal transportation and change in root canal volume were recorded and compared between the three glide path- and nine root canal preparation groups. Canal transportation and centering ability were evaluated over the apical, midroot, and coronal levels (2 mm, 5 mm and 9 mm from the root apex). The results were statistically analysed using a one-way ANOVA for parametric and Kruskal-Wallis H test for non-parametric comparisons. Statistical significance was set at $p< 0.05$.

One G and ProGlider displayed statistically significantly better mean centering ratios than stainless steel K-FlexoFiles at each level examined and for the combined results of the three levels ($p<0.05$).

Apical canal transportation ratio values after glide path enlargement were significantly higher for the K-File group compared to One G and ProGlider ($p<0.05$). At the midroot and coronal levels and for the combined results of the three levels, the canal transportation results were statistically similar for all glide path groups ($p>0.05$).

The volume of dentine removed by the three glide path groups was statistically significantly similar for K-FlexoFiles, One G and ProGlider ($p<0.05$).

No statistically significant difference was found in the mean centering ratios at the apical and midroot levels of the various glide path groups in combination with the shaping instruments ($p>0.05$). However, at the coronal level, centering ratio results following glide path preparation with K-FlexoFiles appeared to affect shaping outcomes for both PTN and OS groups. One Shape performed poorly following all glide path techniques with OG/OS and significantly displayed the worst centering ratio at this level. The results for the combined centering ratio values of the various glide path/shaping groups displayed no statistically significant differences between the different combination groups ($p>0.05$).

Apical canal transportation after shaping was significantly highest for K/OS followed by K/PTN. At the midroot level canal transportation was significantly higher for K/PTN than K/OS and OG/OS, which were statistically similar to each other. Coronal canal transportation after canal shaping was significantly highest for K/PTN followed by K/OS. The most favourable mean combined transportation ratio values of the various glide path/shaping groups were observed in OG/WOG and in PG/WOG groups and the least favourable for the K/OS and the K/PTN groups.

The three groups shaped with ProTaper NEXT exhibited the highest volume of dentine removed with the highest displayed by the PG/PTN group. Statistically, the lowest mean volume of removed dentine was by the PG/WOG group.

In general, results were more favourable after canal preparation with the WaveOne Gold Primary file following any of the three glide path preparation techniques.

Keywords: Glide path, rotation, reciprocation, centering ability, transportation, volume of dentine removed, K-FlexoFiles, One G, ProGlider, OneShape, ProTaper Next, WaveOne Gold

LIST OF FIGURES

Chapter 1

Chapter 3:

Chapter 4:

LIST OF TABLES

Chapter 4

LIST OF ABBREVIATIONS

°	-	Degree/s
%	-	Percentage
μm	-	Micron/s
2D	-	Two-dimensional
3D	-	Three-dimensional
ANOVA	-	Analysis of Variance
Af	-	Austenite finish temperature
BR	-	BioRaCe
CBCT	-	Cone Beam Computed Tomography
CW	-	Clockwise
CCW	-	Counter-clockwise
CT	-	Computed tomography
D0	-	Distance 0 mm from the instrument tip
D1	-	Distance 1 mm from the instrument tip
D3	-	Distance 3 mm from the instrument tip
D4	-	Distance 4 mm from the instrument tip
D14	-	Distance 14 mm from the instrument tip
D16	-	Distance 16 mm from the instrument tip
DOM	-	Dental Operating Microscope
Fig	-	Figure

ISO	-	International Organization of Standardization
K/OS	-	K-Flex file + OneShape
K/PTN -	-	K-Flex file + ProTaper NEXT
K/WOG	-	K-Flex file + Primary WaveOne Gold
M-Wire	-	Memory Nickel-Titanium Wire
micro-CT	-	Micro Computed Tomography
mm	-	Millimetre/s
MIXRAD	-	Micro-focus X-ray Radiography and Tomography Facility
NaOCL	-	Sodium hypochlorite
NECSA	-	Nuclear Energy Corporation of South Africa
NiTi	-	Nickel-Titanium
n	-	Number/s
Ncm	-	Newton per centimetre
OG/OS	-	One G + OneShape
OG/PTN	-	One G + ProTaper NEXT
OG/WOG	-	One G + Primary WaveOne Gold
p	-	Probability
PG	-	ProGlider
PG/OS	-	ProGlider + OneShape
PG/PTN	-	ProGlider + ProTaper NEXT
PG/WOG	-	ProGlider + Primary WaveOne Gold

PTG	-	ProTaper Gold instruments
PTN	-	ProTaper NEXT
PTU	-	ProTaper Universal instruments
s	-	Second/s
SR	-	ScoutRaCe
TRS	-	TRUShape 3D Conforming Files
TF	-	Twisted File

Chapter 1: Introduction and Literature Review

The goal of root canal shaping procedures is to treat apical periodontitis through the removal of infected dentine from root canal walls. Endodontic treatment focuses on eliminating microorganisms by chemo-mechanical preparation of the root canal (Sjøgren et al. 1997; Shuping et al. 2000).

The "ideal chemo-mechanical preparation" refers to an adequately shaped canal that is sufficiently accessible by disinfection solutions. Mechanical canal preparation in the form of root canal shaping not only provides the space for obturation but also supports disinfection by disturbing biofilms that adhere to canal surfaces (Haapasalo et al. 2005).

Excessive dentine removal in a single direction or not equidistantly from the canal centre can result in an uncentered preparation and/or apical canal transportation, which lead to root canal failure.

Correct mechanical instrumentation of the root canal must result in a continuously tapered funnel-shaped canal that corresponds to the original canal anatomy. This objective is often difficult to achieve when an endodontist is faced with the complex internal morphology of curved root canals.

Iatrogenic preparation errors affecting the root canal anatomy remain a problem in this type of canals and can result in apical canal transportation, uncentered preparations, ledge formation, or perforation. Procedural errors that occur during root canal shaping are associated with inferior outcomes (Hülsmann, Peters and Dummer, 2005; Cheung and Liu, 2009).

1.1. Procedural Errors

1.1.1. Ledge Formation

A ledge is an iatrogenically created irregularity or platform on the inside of the greater curvature of the canal. It may form in the original canal path, create a new false canal, and/or block the apical part of the root canal (Lambrianidis, 2009). A ledge that cannot be bypassed impedes instruments and, in some cases, irrigants from entering the apical portion of the canal. This occurrence results in insufficient instrumentation and incomplete obturation (Hülsmann, Peters and Dummer, 2005; Cheung and Liu, 2009). Ledge formation typically occurs when stiff files with sharp inflexible cutting tips are used in a rotational motion in curved root canals. Ledges have been associated with persistent peri-apical infection after endodontic treatment (Jafarzadeh and Abbott, 2007).

Ledging of curved canals is a common procedural error that usually occurs on the outer side of the curvature when instruments are used aggressively, with exaggerated cutting during root canal instrumentation (Lambrianidis, 2009). Ledges are formed either within the original canal path or through creating a new false canal (Fig. 1.1).

Various factors have been implicated in ledge formation; these include tooth and canal location, canal curvature, instrument design, alloy properties, instrumentation techniques, and operator experience. Ledge formation was found to be the most frequently encountered error in a study among patients who received root canal treatment performed by undergraduate students who used hand stainless steel files in a step-back technique (Oikonomou, Spanaki-Voreadi and Georgopoulou, 2007).

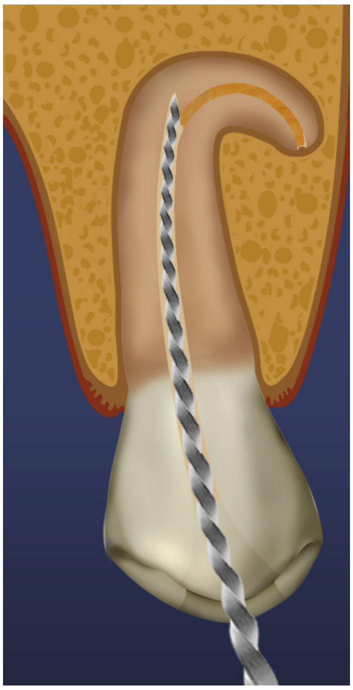

Figure 1.1: Schematic representation of a ledge formed within the original canal path as a result of skipping instrument sizes or erroneous working length estimation

A separate study of ledge formation in maxillary and mandibular first and second molars treated by undergraduate students showed that canal curvature influenced ledge formation more than the other variables examined (Greene and Krell, 1990). As canal curvature increased, so did the number of ledges. Canal curvature in this study was measured by using Schneider's technique. Those canals with a curvature of less than 10° were rarely ledged, whereas canals with a curvature of more than 20° were ledged over 56% of the time (Kapalas and Lambrianidis, 2000).

This same study also showed that canal location influences the incidence of ledging. The mesiobuccal and the mesiolingual canals were more frequently ledged than the distal, lingual, or distobuccal canals (Greene and Krell, 1990). Similar results were reported in another study, which also demonstrated that frequency of ledged root canals was significantly more in molars than in anterior teeth (Eleftheriadis and Lambrianidis, 2005).

According to Lambrianidis (2009), the most common causes of ledge formation are:

- Incorrect or insufficient access cavity preparation that does not allow adequate and unobstructed access to the apical constriction;
- An incorrect assessment of the root canal direction;
- Incorrect length determination of the root canal;
- Use of stainless steel instruments that are not pre-curved within a curved canal;
- Use of over-curved stiff instruments;
- An attempt to retrieve or by-pass a fractured instrument or a foreign object;
- Removing obturation materials during endodontic retreatment;
- An attempt to negotiate a calcified or a very narrow root canal; and
- During post-space preparation after the completion of root canal treatment.

Several authors have highlighted additional causes:

- Forcing and driving the instrument into the canal (Jafarzadeh and Abbott, 2007)
- Using a non-curved stainless steel instrument that is too large for a curved canal (Kapalas and Lambrianidis, 2000);
- Failing to use the instruments in sequential order (Kapalas and Lambrianidis, 2000);
- Rotating the file excessively at the working length (Weine, 1996);
- Inadequate irrigation and/or lubrication during instrumentation (Walton and Torabinejad, 2002)
- Relying too heavily on chelating agents (Weine, 1996); and

- Creating an apical blockage by inadvertently packing debris in the apical portion of the canal during instrumentation (Walton and Torabinejad, 2002).

Files that are stiff and do not remain centered within canals with curvatures can create ledges. Lateral perforations might occur when the ledge is created during initial instrumentation or as a strip perforation when the concave side of the curvature of the root as the canal is straightened out (Jafarzadeh and Abbott, 2007).

1.1.2. Canal Transportation

Canal transportation is a sustained deviation from the original axis of the canal during root canal instrumentation (Fig. 1.2). Apical canal transportation is described as the removal of canal wall structure on the outside curve in the apical half of the canal due to the tendency of files to restore themselves to their original linear shape during canal preparation (American Association of Endodontists, 2012).

As a result, the main axis of the root canal is transported away from its original axis. Other terms for canal transportation include “canal straightening” and “zipping” (Hülsmann, Peters and Dummer, 2005).

Stiff endodontic instruments, particularly large-sized stainless steel files, tend to exert elevated lateral forces in curved canals and can result in straightening, especially in the middle and apical thirds (Lam et al. 1999). This straightening or transportation can create problems with canal cleaning, obturation and, ultimately, healing (Hülsmann, Peters and Dummer, 2005; Cheung and Liu, 2009).

Apical canal transportation can cause enlargement of the apical foramen (Fig. 1.3), which compromises the apical seal (Wu, Fan and Wesselink, 2000). Lack of an apical stop might result in extrusion of irrigants and/or obturation materials and cause irritation to the peri-radicular tissues (Hülsmann, Peters and Dummer, 2005; Schäfer and Dammaschke, 2009).

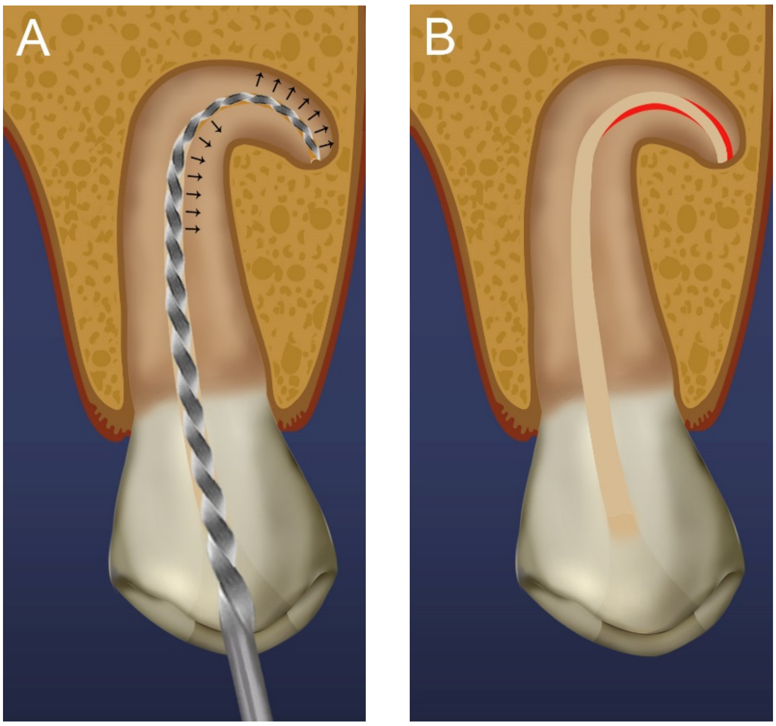

Figure 1.2: Schematic representation of (a) potential directions for transportation in particular zones (as indicated by arrows) when the elastic memory of larger files tend to straighten out the root canal system; (b) the end result of greater removal of dentine (red colour in the illustration) from the external zone of the curve in the apical one third and from the internal zone of the curve in the middle one third of the root canal system (Adapted from Berutti and Castellucci, 2009)

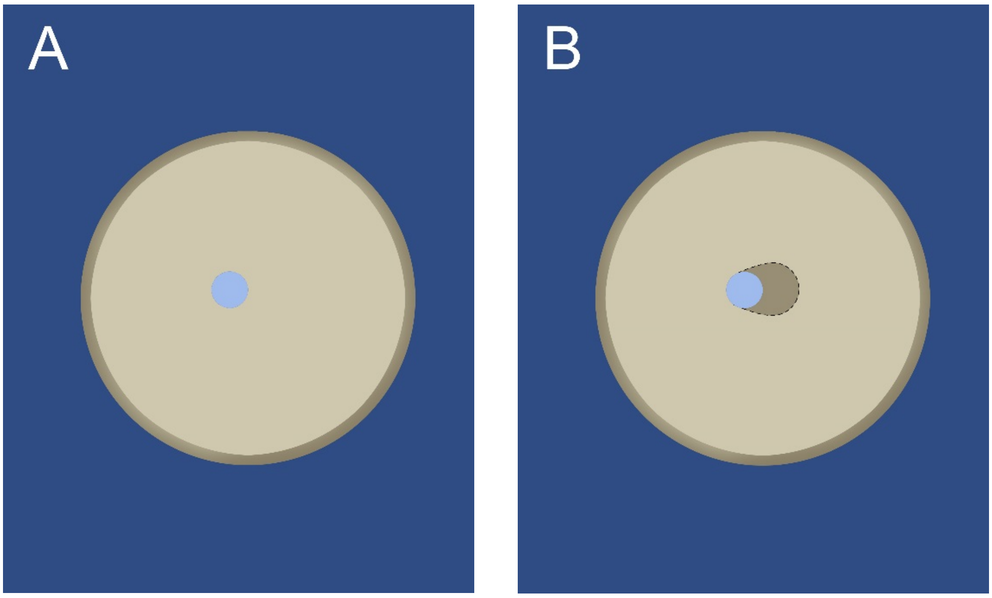

Figure 1.3: Schematic representation of (a) cross section of a root canal system at the level of the apical foramen (apical foramen in light blue); (b) appearance of a teardrop foramen after canal preparation with a straight, non pre-curved instrument. Then original foramen is light blue and the additional dentine removed by the non pre-curved instrument is brown in colour (Adapted from Berutti and Castellucci, 2009)

1.1.3. Perforation

A direct perforation is a channel or communication between the root canal space and surrounding cementum (Fig. 1.4.a). Such a perforation can result in the destruction of cementum and the irritation and/or infection of the periodontal ligament in the surrounding area. As with ledging, perforation of curved canals is associated with stiff instruments with sharp cutting tips used in a rotational motion. Depending on the location, a perforation cannot easily be sealed and/or bypassed, which results in an inadequately prepared and sealed root canal (Hülsmann, Peters and Dummer, 2005; Cheung and Liu, 2009).

A perforation that occurs along the inner wall of a curved root canal is referred to as a "strip perforation". Strip perforation (Fig. 1.4.b) results from over-preparation and straightening along the concavity and is a particular concern in the mesiobuccal roots of maxillary molars and mesial roots of mandibular first molar (Kessler, Peters and Lorton, 1983; Allam 1996). The root walls facing the furcal aspect of roots are often extremely thin and are therefore termed "the danger zone" (Abou-Rass, Frank and Glick, 1980).

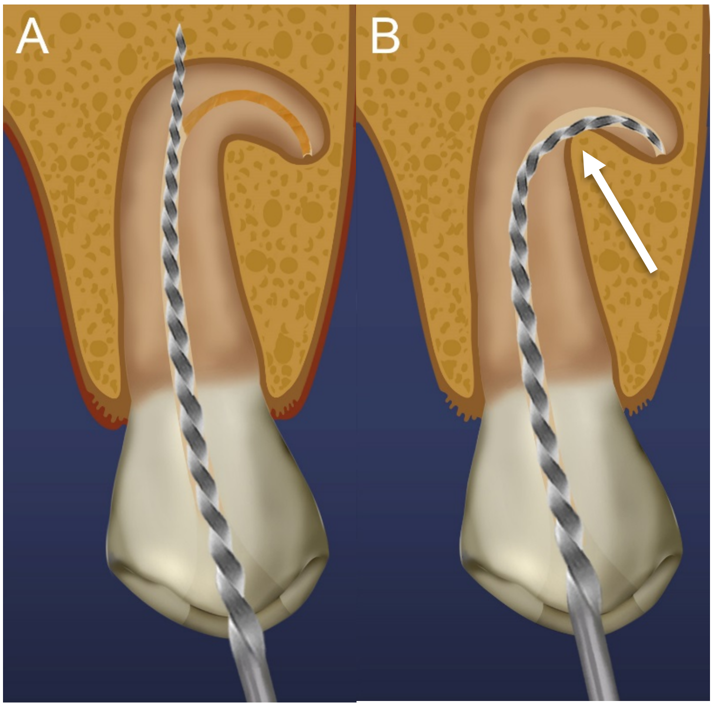

Figure 1.4: Schematic representation of (a) a direct perforation; (b) a strip perforation (arrow)

1.1.4. Uncentered Preparations

The ability of an instrument to stay centered in the canal can be measured by the mean centering ratio (Yamamura et al. 2012). The importance of maintaining preparations that are centered (Fig. 1.5.a) and correspond to the original canal anatomy has been pointed out by (Berutti et al., 2009; Pasqualini et al. 2012).

The study by Pasqualini et al. (2012) examined rotary glide path files and concluded that files with a high root canal centering ability resulted in fewer modifications of the canal curvature and therefore fewer canal aberrations.

Several studies have shown that more flexible instruments produce more centered preparations (Short, Morgan and Baumgartner, 1997; Gergi et al. 2010). Flexibility can be defined as the elastic bending of an endodontic instrument when subject to a load applied at its extremity in the direction that is perpendicular to its long axis (Lopes et al. 2013). Flexibility may influence an instrument's ability to properly shape curved root canals. Inflexible files that cause a deviation from the original canal axis (Fig. 1.5.b) can result in canal straightening, transportation, thinning of the canal wall and perforation.

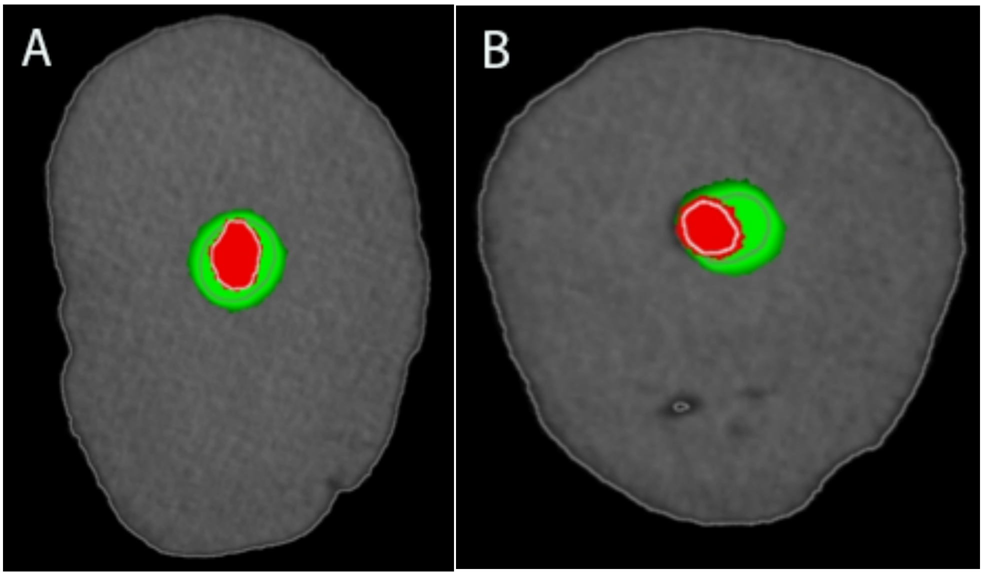

Figure 1.5: Schematic representation of (a) a centered canal preparation; (b) a non-centered canal preparation that can lead to canal straightening, transportation, thinning of the canal wall and perforation (*red* – original canal; *green* – canal after preparation with rotary nickel-titanium instrument)

1.1.5. Instrument Separation

A common problem with the use of rotary files is the potential risk of separation or breakage within the canals (Pereira et al. 2011). In most clinical situations, the breakage of the instrument occurs in the apical third of the canal and the remaining portion is often difficult or impossible to remove (Pruett, Clement and Carnes, 1997; Schrader, Ackermann and Barbakow, 1999). Attempts at removal may even result in other procedural errors like perforation. The fragment that is left behind blocks the root canal system and results in inadequate cleaning, shaping and sealing (Fig. 1.6) (Haikel et al. 1999).

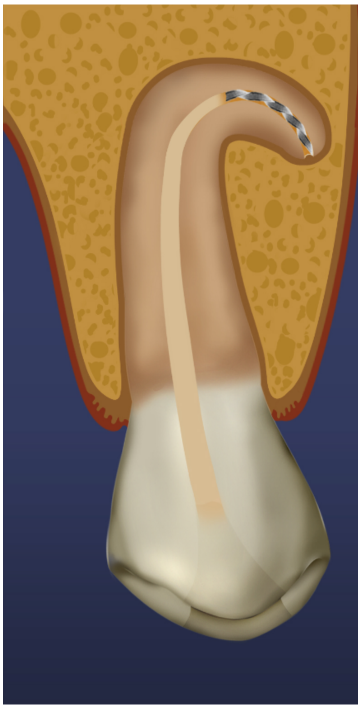

Figure 1.6: Schematic representation of a fractured instrument in a root canal system

Fracture of rotary instruments can occur because of torsional overload (Sattapan et al. 2000), or fatigue through flexure (Al-Hadlaq, AlJarbou and AlThumairy, 2010).

The torsional fracture occurs when the tip or any other part of the instrument binds to the canal walls while the hand piece keeps turning. When this binding occurs and the elastic limit of the metal is exceeded, fracture of the instrument is unavoidable. This type of fracture has been associated with the application of excessive apical force during instrumentation. Fracture resulting from flexural fatigue occurs when an instrument that has already been weakened by metal fatigue is placed under stress. The instrument does not bind to the canal wall but rotates freely until the fracture occurs at the point of maximum flexure (Sattapan et al. 2000). This type of failure is believed to be an important factor in the fracture of nickel-titanium (NiTi) rotary instruments in clinical usage, and might result from their use in curved canals (Pruett, Clement and Carnes, 1997). Various factors have been associated with the fracture of rotary instruments: rotational speed and angle and radius of curvature (Pruett, Clement and Carnes, 1997), instrument design and instrumentation technique (Bryant et al., 1998), torque (Gambarini, 2000), and operator experience (Yared, Bou Daghe and Machtou, 2001).

1.1.6. Apical Bacterial Extrusion

All root canal preparation techniques cause apical extrusion to some degree, in spite of stringent working length control of instruments during debridement. Some amount of debris in the form of dentinal chips, pulp fragments, necrotic debris, microorganisms, and intra-canal irrigants is unavoidably pushed out from the root canal into the peri-apical tissues. The volume of materials that are extruded depends on canal/apical foramen size, instrumentation technique, instrument type, instrument size, and preparation end-point and irrigation solution (Fig. 1.7)(Bürklein and Schäfer, 2012). The extruded material is referred to as the ‘‘worm of necrotic debris’’ and has been linked to peri-apical inflammation and postoperative flare-ups that will likely interfere with healing (Siqueira, 2003). The incidence of flare-ups during root canal treatment is reported to range between 1.4% and 16% (Siqueira et al. 2002).

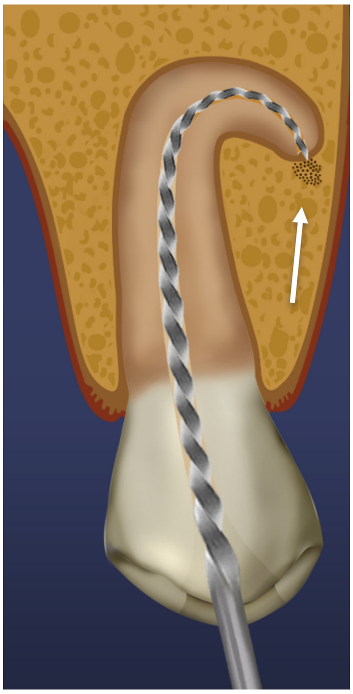

Figure 1.7: Schematic representation of debris extrusion (arrow) through the apical foramen

In asymptomatic chronic peri-radicular lesions a balance exists between host defences and microbial aggression from the root canal microbiota associated with infected canals in peri-radicular tissues (Türker, Uzunoğlu and Aslan, 2015). During root canal treatment procedures if the bacteria are extruded apically, there will be a transient disruption in this balance and the host will mobilise an acute inflammatory response to re-establish the equilibrium. The intensity of this acute inflammatory response depends on the number and/or virulence of the bacteria (Siqueira et al. 2002).

According to Reddy and Hicks (1994), the variation in levels of apical extrusion is primarily due to different root canal preparation techniques and instrument designs. Many studies have shown that techniques involving a push-pull filing motion result in a greater mass of apical debris than techniques that involve some sort of rotational action (McKendry, 1990; Bürklein and Schäfer, 2012). Luisi et al. (2010) have demonstrated that the direction of instrumentation, either in cervico-apical or apico-cervical, is also an important factor influencing apical extrusion. Crown-down techniques, irrespective of whether hand-driven- or engine-driven instruments are used, usually extrude less debris (Al-Omari and Dummer, 1995).

1.2. Metallurgy of Endodontic Files

1.2.1. Stainless Steel

The use of stainless steel K-Files for root canal shaping has largely been replaced by contemporary metal file systems constructed of NiTi, M-Wire, and/or gold-wire. The newer file systems have surpassed large-sized stiff stainless steel files because of their proven flexibility and the associated decrease in procedural errors during shaping. The exclusive use of stainless steel files in curved root canals and at the apical foramen has been shown to cause procedural errors such as canal straightening, zipping, elbow formation, perforation, and instrument separation. These mishaps have been ascribed to the rigidity of the instruments (Pettiette et al. 1999).

Stainless steel files have, however, been recommended for manual glide path enlargement since the early 2000s (Berutti et al. 2004; Walsch, 2004; Mounce, 2005; West, 2006).

The advantages, according to Mounce (2005), of using stainless steel K-Files over rotary NiTi files for glide path enlargement include enhanced tactile sensation, a decreased risk of file fracture, and decreased cost. When a stainless steel K-File is removed from a curved root canal, it stays curved and does not rebound. It is therefore useful in understanding the canal curvatures for subsequent instrumentation (Jerome and Hanlon, 2003; Berutti et al. 2004; Van der Vyver, 2011). The stiffness of stainless steel K-Files allows for negotiation of canal blockages and calcifications (Mounce, 2005; Young, Parashos and Messer, 2007) and no need exists for a dedicated hand piece (Cassim and Van der Vyver, 2013). The disadvantages of enlarging a glide path with hand instruments include operator and hand fatigue; increased enlargement time (Berutti et al. 2009); risk of canal aberrations with the use of larger file sizes (West, 2010); greater change to the original canal anatomy (Pasqualini et al. 2012) and increased apical extrusion of debris (Greco, Carmignani and Cantatore, 2011).

Flexible stainless steel hand files have been recommended for the initial negotiation of canals. These files have a triangular cross-section and are more flexible than those with square cross sections. Flexible stainless steel hand files are generally used in canals that can be negotiated without any difficulty or resistance. The choice between flexible stainless steel files and NiTi hand instruments depends on the clinician's preference (Mounce, 2013). NiTi hand instruments include Mani Flexible Files (Mani, Tochigi-ken), Lexicon Flex SSK Files (Dentsply/Maillefer, Ballaigues, Switzerland), Flexo-file and Senseus ProFinder (Dentsply/Maillefer). According to Peters, Peters and Scho (2003) the extreme flexibility and non-cutting tips of NiTi files render them unsuitable for initial negotiation of the root canal.

1.2.2. Nickel-Titanium

NiTi rotary files are manufactured from the NiTi alloy and were first introduced for endodontic procedures in 1988 (Walia, Brantley and Gerstein, 1988). Numerous studies have shown that the use of NiTi rotary instruments for shaping produces a more centered preparation with less transportation than stainless steel instruments (Hieawy et al. 2015). New NiTi rotary instrument designs are constantly being introduced and have improved cutting and shaping characteristics. NiTi rotary instruments were designed to permit clinicians to perform root canal shaping procedures more easily, more quickly and more predictably and allow for safer and easier preparation of canals with complex anatomical characteristics (Glosson et al. 1995; Garala, et al. 2003). The super-elasticity of the NiTi alloy provides increased flexibility compared to stainless steel and allows the instruments to effectively follow the original path of the root canal (Thompson and Dummer, 1997).

The advent of NiTi rotary instruments allowed for enhanced chemo-mechanical root canal preparation because of their superelasticity and low elastic modulus (Pereira et al. 2011). Superelasticity is associated with the occurrence of a martensitic phase transformation of the alloy upon the application of a certain amount of stress to the austenite phase and the spontaneous reversion of the stress-induced martensite when the stress is released. These properties cause the material to recover its original shape (Thompson, 2000).

Certain NiTi instrument types and their application in canals with sharp curvatures could result in more pronounced deviations from the original canal shape when they are compared to other NiTi types (Bergmans et al. 2001; Hülsmann, Herbst and Schäfers, 2003; Berutti et al. 2009).

Deviation of the instrument from the canal axis during shaping causes excessive dentine removal in a single direction and results in apical canal transportation and, perhaps, large areas of the root canal surface remaining unprepared. These risks are exacerbated by the presence of curvatures within the root canal system. However, when they are compared with manual preparation techniques, NiTi files have been shown to significantly decrease these procedural errors, especially in the apical area of the curved canal (Setzer, Kwon and Karabucak, 2010). These instruments allow for consistent and efficient canal shaping with relatively few instruments (Glosson et al. 1995; Thompson and Dummer, 1997).

Despite the many advantages of using NiTi rotary instruments, the risk of instrument fracture within the canal remains a problem during endodontic treatment. The flexural (bending) stresses and torsional (shear) stresses exerted on the file are the primary causes of these breakages (Berutti et al., 2003; Parashos and Messer, 2006). According to Sattapan, Palamara and Messer (2000) extreme torsional stress is the main cause of instrument fracture. Torsional failure might occur in case of shear stresses exceeding the elastic limit of the alloy, producing plastic deformation and eventually fracture (Parashos and Messer, 2006). Torsional stresses can be avoided by careful clinical considerations and instrument choice. Flexural stress, however, depends on the original anatomy of the canal and therefore cannot be influenced significantly by the clinician.

Factors that contribute to an increase in stresses include excessive pressure on the hand piece (Kobayashi, Yoshioka and Suda, 1997), a wide area of contact between the canal walls and the cutting edge of the instrument (Peters et al. 2003); and the canal section being smaller than the dimension of the non-active- or non-cutting tip of the instrument (Blum et al. 1999).

In most clinical situations the breakage of the instrument occurs in the apical third of the canal and the remaining portion is often difficult to remove (Berutti et al. 2003; Peters, 2004). The fragment that remains blocks the root canal system and impedes adequate cleaning, shaping and sealing (Haikel et al. 1999). The NiTi rotary instrument rotates continuously within the root canal system and its durability is directly proportional to the working stress it undergoes (Yared, Bou Dagher and Machtou, 1999; Gambarini, 2001). Working stress is closely related to the number of cycles performed (Pruett, Clement and Carnes, 1997).

1.2.3. M-Wire

As far back as 1982, Miyazaki et al. reported that superelasticity of nickel-rich NiTi alloys can be improved by suppressing slip during stress-induced martensitic transformation by raising the critical stress for slip. Two mechanisms are available to raise the critical stress for slip in nickel-rich NiTi alloys: (i) precipitation hardening and (ii) hardening because of a high density of thermally rearranged dislocations. A proprietary method of thermo-mechanical treatment of 508 Nitinol wire produced memory nickel-titanium wire (M-Wire) (Nitinol Devices & Components, Inc., Fremont, California, USA), which resulted in a material that includes amounts of both the R-phase and the B190 martensitic phases while maintaining the alloy's superelasticity (Johnson et al. 2008; Pereira et al. 2011).

Memory nickel-titanium wire is constructed by thermo mechanically treating NiTi to increase flexibility and resistance to cyclic fatigue. According to Johnson et al. (2008) this process makes M-Wire files almost 400% more resistant to cyclic fatigue than conventional NiTi files and, in this way, decreases the risk of file fracture.

A study compared the cyclic flexural fatigue resistance of GT Series X files (Dentsply Sirona) made from M-Wire with GT (Dentsply Sirona) and Profile (Dentsply Sirona) made from a regular nickel-titanium alloy (Al-Hadlaq, AlJarbou and AlThumairy, 2010). The findings of this study demonstrated that size 30/04 NiTi rotary files made from the M-Wire alloy exhibit superior cyclic flexural fatigue resistance than files of similar design and size made from the regular NiTi alloy. The extreme flexibility and resistance to cyclic fatigue have been attributed to M-Wire's control memory feature. Shen et al. (2011) compared the chemical composition, transformation temperatures, and Vickers micro-hardness measurements of conventional NiTi and M-Wire. The authors concluded that M-Wire possesses physical and mechanical properties that can render endodontic instruments more flexible and fatigue resistant than those made with conventionally processed NiTi wires. The study by Pereira et al. (2011) study demonstrated that the two wires presented almost the same chemical composition, close to the 1:1 atomic ratio with the β-phase dominating. M-Wire exhibited both B19 martensite and the R-phase with higher transformation temperatures than the conventional NiTi wire demonstrated. In fact, transformation temperatures of the NiTi wire were below room temperature. Average Vickers micro hardness values were similar for M-Wire and the conventional NiTi. However, the stress at the transformation plateau in the tensile load-unload curves was lower and more uniform in the M-Wire, which also showed the smallest stress hysteresis and apparent elastic modulus. Several authors have found significantly higher fatigue resistance, torsional strength, flexibility, and higher deformation before failure when M-Wire has been compared with conventional NiTi (Shen et al. 2011; Ye and Gao, 2012; Braga et al. 2014).

1.2.4. Gold-Wire

Gold-Wire is a new super-metal manufactured from a metal produced at the phase-transition point between the martensite and austenite phases. This super-metal is completed by thermal processing and post-machining procedures (Elnaghy and Elsaka, 2016a; Uygun et al. 2016). According to the manufacturer, the Gold version of WaveOne is 80% more flexible, 50% more resistant to cyclic fatigue, and 23% more efficient than its predecessor manufactured from M-Wire (Webber, 2015; Ruddle, 2016).

1.2.4.1 Mechanical Properties

Nickel-titanium exists in two different crystal phases: martensite and austenite. These phases are temperature dependent and exhibit diverse properties (Otsuka and Ren, 2005). When martensitic NiTi is heated it begins to change to austenite and, once converted to austenite, the alloy will have completed its shape memory transformation and will display its super-elastic characteristics. The temperature at which this phenomenon is complete is called the "austenite finish temperature" (Af) (Yoneyama and Kobayashi, 2009).

ProTaper Gold (PTG) (Dentsply Sirona, Baillagues, Switzerland) instruments are manufactured using with the use of heat treatment technology. PTG files have a 2-stage specific transformation behaviour and high Af temperatures. This contrasts with the ProTaper Universal (PTU) system (Dentsply Sirona), the conventional NiTi counterpart to PTG, which has 1-stage transformation (Elnaghy and Elsaka, 2016b; Topcuoglu et al. 2016). The Af temperature for PTU files is below body temperature (between 16°C and 31°C), while the Af temperature for the new PTG files is 55°C – higher than body temperature and similar to that of M-Wire (Hieawy et al. 2015). This means that during clinical use PTU files are in the austenite phase, which renders the material hard and strong. The PTG files, however, remain in the martensite phase during clinical use, which makes it soft and ductile, and able to be pre-curved.

1.2.4.2 Cyclic Fatigue and Bending Resistance

According to Gambarini (2001) endodontic instruments with improved flexibility will reduce iatrogenic errors resulting from canal transportation and enhance the efficiency and safety of root canal preparation. Fracture of NiTi rotary instruments occurs as a result of cyclic flexural fatigue or torsional failure (Plotino et al. 2009). Cyclic flexural fatigue occurs when the instrument rotates in a curved canal by repeated compressive and tensile stresses. Torsional failure occurs when the tip of the instrument is locked in the canal while the shank continues to rotate. Fracture of the tip becomes inevitable once the elastic limit of the metal is surpassed by the torque of the hand piece (Cheung, 2007; Plotino et al. 2009).

A recent study by Plotino et al. (2017) compared the influence of temperature on PTU and PTG and found that PTU performed statistically better at room temperature than at intra-canal temperature because its transformation temperature was between room and intra-canal temperature. These authors concluded that the gold metal processing of PTG instruments, which has a much higher transformation temperature, were not statistically affected by the increase of temperature during cyclic fatigue testing. Plotino et al. (2017) also attributed the results to the two-stage transformation behaviour of PTG, austenite-reverse phase-martensite, because the reverse phase could be considered a potential martensitic phase (Hieawy et al. 2015; Elnaghy and Elsaka, 2016a).

The authors also concluded that the gold heat treatment of the NiTi alloy increases the resistance to cyclic fatigue in comparison with the resistance to cyclic fatigue of the traditional NiTi alloy of ProTaper files for both sizes tested (ie. S1 and F2). These results are similar to those of Elnaghy and Elsaka (2016c), who examined the mechanical properties of PTG in comparison to PTU. Elnaghy and Elsaka's study found that the PTG instrument had improved flexibility and resistance to cyclic fatigue compared to PTU. PTU instruments had improved resistance to torsional stress and micro-hardness compared to PTG. Kaval and Capar (2017) compared the cyclic fatigue and torsional resistance of Hyflex EDM (Coltene/Whaledent, Altstätten, Switzerland), PTG, and PTU instruments. They concluded that Hyflex EDM files demonstrated significantly higher cyclic fatigue resistance but that in spite of their similar cross-sectional design, PTG instruments presented higher cyclic fatigue and torsional resistance than PTU instruments.

Topcuoglu et al. (2016) compared the cyclic fatigue resistance of WaveOne Gold (WOG)(Dentsply Sirona), Reciproc (VDW, Munich, Germany) and WaveOne files (Dentsply Sirona) in canals with a double curvature. WaveOne Gold primary files were found to exhibit greater cyclic fatigue resistance than

Reciproc R25 and WaveOne Primary in an artificial canal with an S-shape. In 2016, Elsaka, Elnaghy and Badr evaluated the torsional and bending resistance of WaveOne Gold (Dentsply Sirona), Reciproc (VDW, Munich, Germany) and Twisted File Adaptive (Axis/SybronEndo, Orange, CA, USA) instruments. Measurement was calculated through the securing of the apical 3 mm of each instrument and the application of a constant rotation of 2 rpm to the instrument with the use of a torsiometer.

The results of this study showed that WaveOne Gold exhibited higher resistance to torsional stress and flexibility compared to Reciproc and Twisted File Adaptive instruments. Elsaka, Elnaghy, and Badr ascribed these results to the alloy from which the instrument is manufactured and different cross-sectional design.

In a separate study, Elnaghy and Elsaka (2016a) compared the cyclic fatigue resistance of WaveOne Gold (Dentsply Sirona) and Reciproc (VDW) reciprocating instruments during immersion in sodium hypochlorite (NaOCl) and saline solutions at body temperature. The results of the study demonstrated that immersion of WaveOne Gold and Reciproc reciprocating instruments in saline and NaOCl solutions decreased their cyclic fatigue resistance but that the fatigue resistance of WaveOne Gold instruments was higher than that of Reciproc instruments.

In another study by Elnaghy and Elsaka (2016b) the mechanical properties of TRUShape 3D Conforming Files (TRS) (Dentsply Sirona), a NiTi instrument, and ProTaper Universal instruments (PTU), ProTaper Gold instruments (PTG), and ProTaper NEXT (PTN) (Dentsply Sirona) were assessed and compared. The authors concluded that TRS instruments had lower resistance to cyclic fatigue and were less flexible than PTG and PTN instruments. The TRS, PTG, and PTU instruments had lower resistance to torsional stress than PTN instruments. The TRS and PTG instruments had comparable surface micro-hardness.

These results are similar to those of Uygun et al. (2016) who evaluated the cyclic fatigue resistance among PTG, PTN, and PTU instruments at various levels. The PTG instruments were found to be the most resistant 5 mm and 8 mm from the tip. The PTU files demonstrated the lowest cyclic fatigue resistance at all levels.

1.3. Glide Path Systems

The endodontic glide path is defined as a smooth, patent passage from the coronal orifice of the canal to the radiographic terminus or electronically determined portal of exit (West, 2006). A successful glide path is an uninterrupted passage that can be reproduced when small-size files are used in sequence in the canal (Khatavkar and Hegde, 2010).

Apical pre-enlargement tends to minimise biomechanical preparation failures such as canal transportation and ledge formation at different levels and also reduces the number of pecking motions required to achieve the working length (Elnaghy and Elsaka, 2014; Kirchhoff et al. 2015). The glide path can be achieved with both hand- and rotary instruments (De-Oliveira Alves et al. 2012). The use of hand files, however, has been shown to be more time consuming, particularly in teeth with constricted and/or severely curved canals (D’Amario et al. 2013). Over the last few years, research has repeatedly shown that NiTi glide path rotary instruments are capable of achieving a safe and predictable glide path in comparison to hand files (De-Oliveira Alves et al. 2012; D’Amario et al. 2013; Berutti et al. 2014; Elnaghy and Elsaka, 2015a).

Mechanical (NiTi) glide path systems have been shown to improve the glide path prior to the use of NiTi shaping instruments (Ruddle, 2002; Gergi et al. 2010). Systems like the ProGlider (Dentsply Sirona), and G-Files (Micro-Mega, Besançon, France) are said to preserve the original canal anatomy and cause fewer aberrations and modifications of canal curvature. Predictable radicular cleaning and shaping is more likely after an established glide path has been formed that is smooth and centered from the root canal orifice to the physiologic terminus.

Glide path enlargement allows for more effective and safer rotary shaping because it guarantees that the root canal diameter is sufficiently large to receive the first shaping instrument (Berutti et al. 2004; Varela-Patiño et al. 2005; Ruddle, 2014).

A number of studies have illustrated the many benefits of glide path formation, which include decreased canal aberrations and decreased risk of shaping file fracture (Roland et al. 2002; Berutti et al. 2004; Varela-Patiño et al. 2005; Nahmias, Cassim and Glassman, 2013). According to West (2010) a successful glide path will most likely be maintained by larger shaping instruments and must then be the starting point of all root canal treatment.
The converse, therefore, follows: procedural errors initiated during glide path enlargement are more likely to be exacerbated during shaping by larger NiTi rotary files, in this way affecting the clinical outcome. Any instrumentation that removes excessive dentine and changes the canal anatomy significantly will cause iatrogenic preparation errors and may adversely affect the strength of the tooth (Sathorn, Palamara and Messer, 2005; Versluis, Messer and Pintado, 2006).

1.3.1. Stainless Steel K-Files Manual

According to West (2010) a glide path is present when a size 0.10 stainless- steel K-File fits loosely in the canal. Stainless steel K-Files (Fig. 1.8) have a constant taper of 2%. West advocates using these files in a vertical in-and-out motion with initial amplitudes of 1mm, gradually increasing as the dentine wall wears away and the file advances apically. West stresses that the file must not be forced apically through any obstructions and suggests oscillating the file back and forth in 30° to 60° increments to simulate a “watch-winding” motion to remove restrictive dentine in narrow canals. Van der Vyver (2011) recommends that the file be withdrawn in 1 mm increments from 1 mm to 5 mm while the file is ensured of the ability to slide to working length to confirm the glide path after each increment.

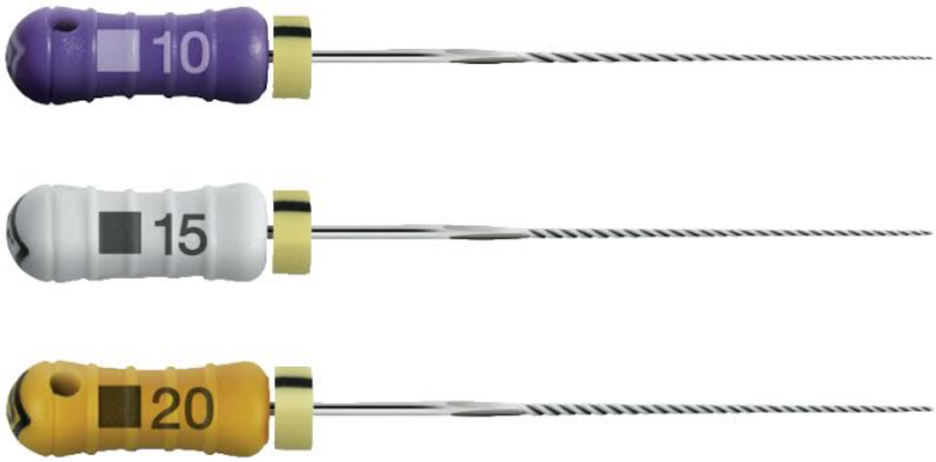

Figure 1.8: Stainless steel K-Files sizes 10 (purple), 15 (white) and 20 (yellow)

Schilder (1974) recommended pre-curving instruments for use in curved canals. This technique allows the "watch-winding" motion in order to create space for larger curved files to follow by advancing the file just short of maximum resistance. Then the file is removed while it is being simultaneously rotated in a clockwise direction.

The many advantages of using stainless steel K-Files over NiTi files for glide path enlargement include improved tactile sensation with a heightened appreciation of anatomical curvatures; decreased risk of file fracture and decreased cost associated with stainless steel files; and the elimination of the use of a hand piece (Jerome and Hanlon, 2003; Berutti et al. 2004; Mounce, 2005; Cassim and Van der Vyver, 2013).

Canal obstructions can be bypassed and an appreciation of the anatomy of curved canals gained by using stiff stainless steel K-Files (Jerome and Hanlon, 2003; Berutti et al. 2004; Young, Parashos and Messer, 2007). The disadvantages include operator fatigue and hand fatigue, a longer operational time (Berutti, et al. 2009); the risk of canal irregularities with the use of larger file sizes (West, 2010); and increased apical extrusion of debris (Greco, Carmignani and Cantatore, 2011).

1.3.2. Stainless Steel K-Files Reciprocation

The M4 safety hand piece (SybronEndo, Glendora, CA, USA) was developed so that stainless steel K-Files could be used in a reciprocating motion for glide path enlargement (Fig. 1.9). The hand piece features a 4:1 gear reduction, oscillates 30° in both clockwise and counter-clockwise directions, in this manner replicating manual hand file watch winding. According to the manufacturer, this watch-winding motion keeps the file loose inside the canal, reduces torsional stress and metal fatigue, and permits safe negotiation while the operator controls the apical pressure. The NSK Ti-Max Ti35L 10:1 (Nakanishi Inc, Tokyo, Japan), Endo-Gripper (Moyco/Union Broach; Montgomeryville, USA) and the NSK TEP-E10 R (Nakanishi Inc.) are similar to the M4 hand piece but with a 45° and 90° horizontal rotational motion, respectively.

A study by Gambarini et al. (2015) compared the cyclic fatigue resistance between stainless steel K-Files used in a reciprocating motion and NiTi PathFile rotary instruments in artificial curved canals. The aim of the study was to evaluate whether stainless steel instruments could benefit from a reciprocating motion during their enlargement of the glide path, given that that reciprocation can improve fatigue resistance of NiTi instruments. The stainless steel K-Files used with the M4 hand piece showed a significantly greater resistance to cyclic fatigue in comparison to the NiTi rotary PathFiles.

Clinically, reciprocation is used after the canal has been negotiated to the working length by hand and with the use of a small-size K-File. Reciprocation proceeds with the first file that binds at working length. Reciprocation is useful for the early enlargement of calcified canals and the elimination of iatrogenic ledges (Mounce, 2013). Once the stainless steel K-File can negotiate around the ledge, it is left in place and reciprocated, as suggested by Mounce (2013).

Figure 1.9: M4 Safety Reciprocating Hand Piece (SybronEndo) with a size 08 stainless steel K-File attached

The advantages of using a stainless steel K-File in a reciprocating hand piece for glide path enlargement include a reduction in preparation time; reduced operator and hand fatigue; and reduced risk of instrument separation compared with rotary NiTi methods (Kinsey and Mounce, 2008). The disadvantages include the need for a dedicated hand piece; the risk of apical transportation with files larger than a 15 K-File (Van der Vyver, 2011); the risk of excess dentine removal as a result of the clinician instrumenting the canal for longer than necessary (Wagner et al. 2006); the risk of apical extrusion of debris if the hand piece is forced apically (Kinsey and Mounce, 2008); and decreased tactile sensation.

1.3.3. Rotary Glide Path Instruments

1.3.3.1. PathFiles (Dentsply Sirona)

In 2009, Dentsply Sirona introduced a three-file rotary NiTi system specifically for glide path enlargement. Each file has a taper of 2% and exhibits a square cross-section. These features, according to the manufacturer, ensure flexibility, improved cutting efficiency, and render these files more resistant to cyclic fatigue. The tip of each file is non-cutting, which reduces the risk of ledge formation. PathFile no.1 (purple) has an ISO 13 tip size, PathFile no.2 (white) ISO 16 tip size and PathFile no.3 (yellow) has an ISO 19 tip size (Fig. 1.10).

The gradual increase in tip size facilitates progression of the files. The manufacturer suggests using PathFile no.1 only after a size 10 stainless steel K-File has been used to explore the root canal to working length (Berutti et al. 2009).

Figure 1.10: PathFile no.1 (purple), PathFile no.2 (white) and PathFile no.3 (yellow) (Dentsply Sirona)

There are numerous studies on the efficacy of PathFiles. Berutti et al. (2009) have shown that PathFiles maintain the original canal anatomy with less modification of canal curvature and fewer canal aberrations than manual glide path enlargement performed with stainless steel K-Files.

Pasqualini et al. (2012) used micro-computed tomography (micro-CT) to examine curved root canals where glide paths were prepared to full working length with the use of PathFiles and stainless steel K-Files. These researchers concluded that PathFiles have a higher root canal centering ability, cause fewer modifications of the canal curvature and fewer canal aberrations and, therefore, maintain the original canal shape considerably better than stainless steel K-Files do. In 2014 Nakagawa et al. studied the flexibility and torsional resistance of rotary NiTi PathFile, RaCe ISO 10 (FKG Dentaire, La Chaux-de-Fonds, Switzerland), ScoutRaCe (FKG Dentaire) and stainlesssteel hand K-Files. The results of this study demonstrated that the NiTi rotary glide path enlargement files were more effective at enlarging the glide path with fewer aberrant modifications to canal anatomy. PathFiles were shown to be the most flexible and the least torque resistant compared with ScoutRaCe and RaCe ISO 10 instruments. A study examining the influence of a glide path on canal curvature and axis modification after instrumentation with WaveOne Primary reciprocating files (Dentsply Sirona) showed significantly fewer canal modifications when WaveOne was used after glide path enlargement (Berutti et al. 2012b).

1.3.3.2. RaCe ISO (FKG Dentaire)

RaCe ISO 10 (FKG Dentaire) (Fig. 1.11) is a three-file system with progressively increasing tapers: 2% (yellow ring), 4% (red ring) and 6% (blue ring). All have the same apical diameter of 0.1 mm. These files have been indicated for constricted obliterated canals and for abrupt coronal curvatures (Debelian and Trope, 2012).

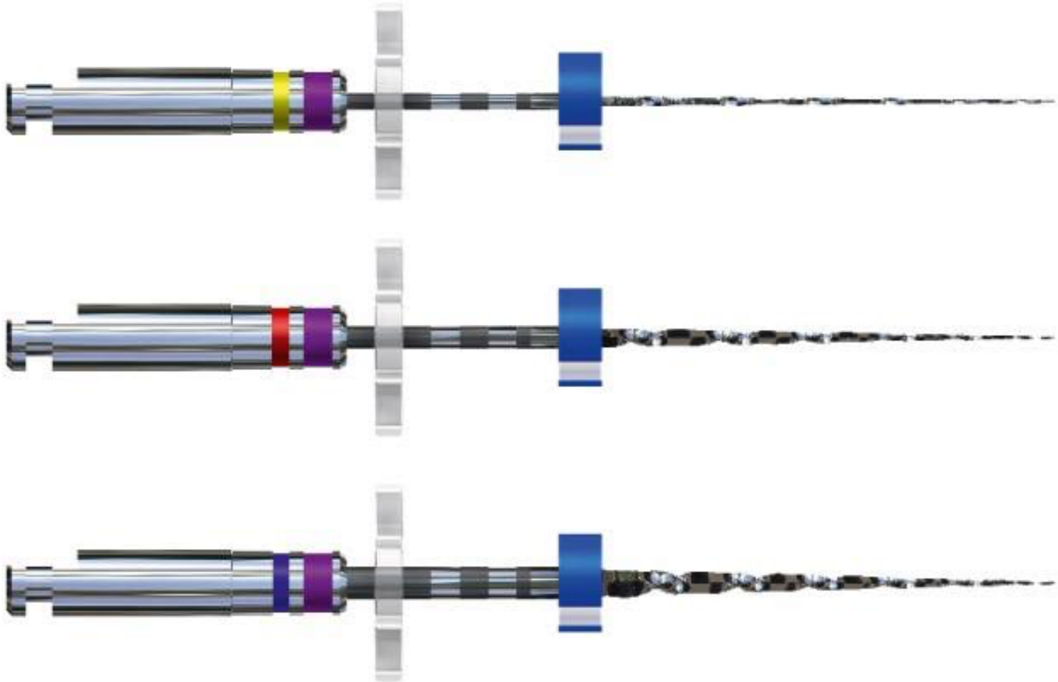

Figure 1.11: RaCe ISO 10 (FKG Dentaire) 2% (yellow), 4% (red) and 6% (blue) tapered files

1.3.3.3. ScoutRaCe (FKG Dentaire)

ScoutRaCe (FKG Dentaire) (Fig. 1.12) is a two-file system with each file exhibiting a 2% taper, a triangular cross section, alternating cutting edges and a non-cutting tip. They are available in ISO tip size 10 (purple), 15 (white) and 20 (yellow) and are used in sequence following initial canal exploration with a size 06 or 08 K-File to working length (Cassim and Van der Vyver, 2013).

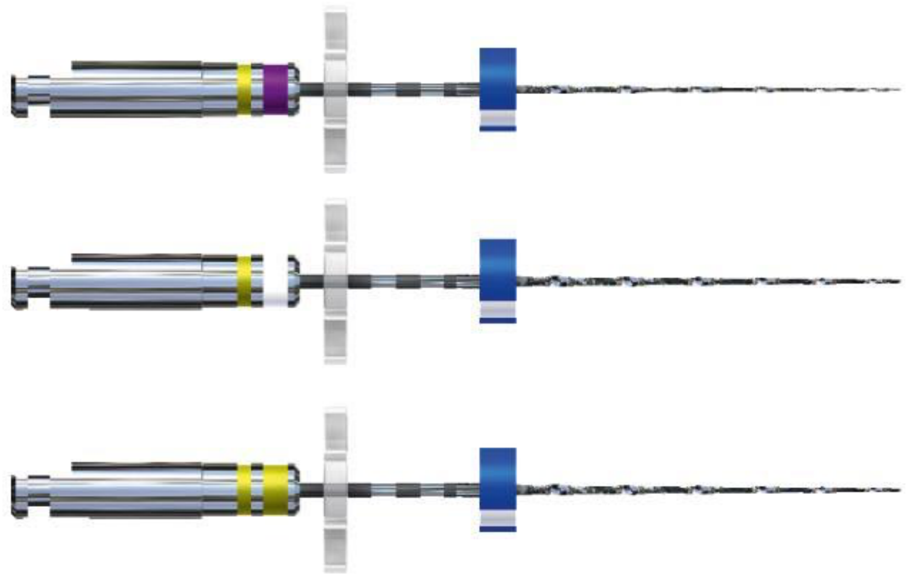

Figure 1.12: ScoutRaCe files (FKG Dentaire) ISO size 10 (purple), ISO size 15 (white) and ISO size 20 (yellow)

Ajuz et al. (2013) examined changes in canal curvature and incidence of canal irregularities after glide path enlargement with stainless steel K-Files, PathFiles and ScoutRaCe files. PathFile instruments generated less modification of curvature and fewer canal aberrations. ScoutRaCe, however, showed significantly better performance in shaping double-curved canals. A study by Lopes et al. (2012) compared the mechanical properties of C-Pilot (VDW), PathFile (Dentsply Sirona), and ScoutRaCe. PathFile instruments showed the highest resistance to cyclic fatigue, and ScoutRaCe files exhibited the highest angular deflection to fracture.

1.3.3.4. G-Files (Micro-Mega, Besançon, France)

The G-File system (Micro-Mega) consists of two files: the G1 file (red ring) with an ISO 12 tip size; and the G2 file (white ring) with an ISO 17 tip size (Fig. 1.13).

The files have a 3% taper along the length, an evolving cross section that varies along the instrument, and non-cutting asymmetrical tips to aid in the progression of the file. The cross section has blades on three different radii to aid in the removal of debris and to reduce torsion. The manufacturer recommends their use after a size 10 hand file has been used to explore the canal to working length.

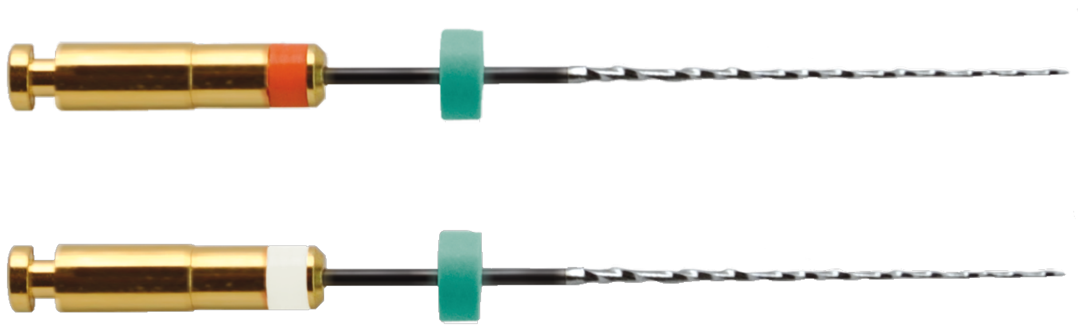

Figure 1.13: G-Files (Micro-Mega) G1 (red ring) and G2 (white ring)

1.3.3.5. ProGlider (Dentsply Sirona)

The ProGlider (Dentsply Sirona) (Fig. 1.14) is single mechanical glide path file manufactured using M-Wire. The ProGlider file has a square cross section with a diameter of 0.16 mm at D0 and 0.82 mm at D16 and is progressively tapered from 2% to 8% over its length. According to its manufacturers, the file ensures a controlled, smooth, inward-cutting action that produces a smoother glide path. A small-size stainless steel K-File is initially used to scout, expand, and refine the internal walls of the canal. Once the canal can be manually reproduced, the single ProGlider file may be used to expand the working width in preparation for shaping procedures (Van der Vyver, 2014).

A study by Van der Vyver, Paleker and Jonker (2015) compared the preparation times of glide path enlargement using stainless steel K-files, PathFiles (Dentsply Sirona), X-Plorer files (Clinician's Choice Dental Products Inc., New Milford, USA) and the single ProGlider file in plastic blocks.

The ProGlider file demonstrated significantly shorter glide path enlargement times with a mean preparation time of 11.3 seconds. A more recent study compared the preparation times of glide path enlargement using stainless steel K-Files, G-Files (Micro-Mega, Besançon, France) and the single ProGlider file in curved mesial canals of mandibular molars (Paleker and Van der Vyver, 2017). The ProGlider file and G-Files demonstrated significantly shorter glide path enlargement times with a mean preparation time of 27.95 and 41.87 seconds respectively. K-Files exhibited a mean preparation time of 74.92 seconds.

Figure 1.14: ProGlider file (Dentsply Sirona)

In this study by Paleker and Van der Vyver, micro-CT was used to compare the centering ability and apical canal transportation of these three file groups. Both the NiTi rotary glide path enlargement systems used here exhibited significantly less apical canal transportation than the stainless steel K-files. The ProGlider file, however, exhibited a superior centering ability to that of both stainless steel K-Files and NiTi G-Files at the point of maximum curvature. In 2014, Elnaghy and Elsaka used Cone Beam Computed Tomography (CBCT) imaging to compare the volume of removed dentine, transportation, and the centering ability of the ProTaper NEXT (Dentsply Sirona) system with and without glide path enlargement. The authors examined transportation values at 3-, 5-, and

7 mm levels. Their results showed significantly reduced mean transportation values at the 3 mm- and 5 mm level in the ProGlider-ProTaper NEXT group. The conclusion was reached that using this method resulted in better performance with fewer canal aberrations than instrumentation performed with PathFile-ProTaper NEXT or ProTaper Next only.

1.3.3.6. One G (Micro-Mega)

The One G instrument (Micro-Mega) was launched in 2015 as a single file system for glide path enlargement. This NiTi rotary glide path file has a 3% taper with three cutting edges situated on three different radii relative to the canal axis, which, according to the manufacturers, enhances the cutting action and allows for more space for debris elimination. The One G instrument has an ISO size 0.14 non-cutting tip that reduces the risk of ledge formation (Fig. 1.15) and a variable pitch between the cutting edges that is said to limit the screwing effect.

Figure 1.15: One G file (Micro-Mega)

Ha *et al.* (2015) compared the One G prototype with the G2 file (Micro-Mega) and found that One G had a higher cyclic fatigue resistance. These authors concluded that the increased fatigue resistance and flexibility might enable maintenance of the original canal anatomy during glide path enlargement, as well as reduced risk of ledge formation or transportation. The minimised contact area from the shaft of 3% taper was reported as possibly reducing the torque during instrumentation.

1.3.3.7. X-Plorer Canal Navigation NiTi Files (Clinician's Choice Dental Products Inc., New Milford, USA)

The X-Plorer Canal Navigation NiTi Files (Clinician's Choice Dental Products Inc.) (Fig. 1.16) consists of four instruments, available with distinctive cutting surfaces, tapers and cross-sections. The cutting surface of each file is limited to the apical 10 mm of the file. This feature decreases torsion and contact with the surrounding surface and, conversely, increases tactile feedback.

Figure 1.16: X-Plorer Canal Navigation NiTi Files (Clinician's Choice Dental Products Inc.) ISO 15 tip (white ring, marked 01), ISO 20 tip (yellow ring, marked 01), ISO 20 tip (yellow ring, marked 02), and ISO 25 tip (red ring, marked 02)

The manufacturer recommends using the X-Plorer series after a size 08 or size 10 stainless steel K-File has been used to penetrate the canal to working length. The first X-Plorer file has an ISO 15 tip size and a 1% taper with a triangular cross section. The second has an ISO 20 tip size with a 1% taper and square cross section. The third has an ISO 20 tip size with a 2% taper and square cross section.

The fourth has an ISO 25 tip size and a 2% taper with, again, a square cross section. The reduced taper increases flexibility and facilitates apical progression of the files. The X-Plorer files are available as rotary and hand files and have non-cutting tips each with a tip angle of 75° (Nahmias, Cassim and Glassman, 2013). Recently, a fourth file was introduced specifically for both clinicians who prefer to establish a working length up to a size 25 and those who want to have a larger diameter at working length before using rotary shaping files in tiny canals.

1.3.4. Reciprocating Glide Path Instruments

1.3.4.1. WaveOne Gold Glider (Dentsply Sirona)

The WaveOne Gold Glider (Dentsply Sirona) (Fig. 1.17) was launched in 2017. The file is a reciprocating NiTi file designed for glide path enlargement prior to shaping canals with a Primary WaveOne Gold file.

The WaveOne Gold Glider is a single-use sterile instrument and re-use is not allowed. The file has an ISO size 15 tip size with a variable taper of between 2% (D0) and 6% (D16) and a parallelogram shaped cross sectional design. The tip of the file is semi-active and the active cutting flute length is 16 mm.

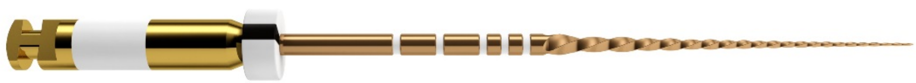

Figure 1.17: WaveOne Gold Glider (Dentsply Sirona)

The manufacture of the WaveOne Gold Glider entails the use of NiTi wire subjected to a post-manufacturing thermal process. During this process, a new phase-transition point between martensite and austenite is identified in order to produce a file with super-elastic NiTi metal properties. This process gives the file a gold finish and renders it more flexible and more resistant to cyclic fatigue compared to conventional NiTi and M-Wire alloys (Webber, 2015).

1.3.4.2. R-Pilot (VDW, Munich, Germany)

The R-Pilot instrument (VDW) (Fig. 1.18) is a glide path instrument manufactured from M-Wire and is used in reciprocating motion to prepare the root canal system before the shaping with a rotary or a reciprocating instrument. The R-Pilot instrument has a constant taper of 4%, an ISO tip size of 12,5 and an s-shaped cross section. It is a single-use instrument designed for use in no more than one molar. The R-Pilot instrument can be used only in a reciprocating motion with a designated drive system using that uses the original Reciproc (VDW) settings. Failure to do so, according to the manufacturers can lead to instrument fracture and misuse. The instrument is not recommended for use in canals with abrupt apical curvatures in the apical region.

Figure 1.18: R-Pilot (VDW)

1.4. Rotating Root Canal Shaping Systems

1.4.1. BioRaCe (FKG Dentaire)

BioRaCe (FKG Dentaire)(Fig. 1.19) is a rotary NiTi shaping system that consists of instruments that are manufactured from a conventional austenite NiTi electro-polishing surface treatment, have a noncutting safety tip, and a triangular cross section with alternating cutting edges (Lopes et al. 2010). The basic set has six instruments: BR0 (25/08), BR1 (15/05), BR2 (25/04), BR3 (25/06), BR4 (35/04) and BR5 (40/04). According to the manufacturer, the varying diameters and tapers of this sequence reduce the contact area of each instrument with the canals walls, which minimises stress and provides the ability to safely reach the working length.

A recent study compared the shaping ability of two rotary file systems; BioRaCe and ProTaper NEXT (PTN) during the preparation of curved root canals and in extracted teeth with the use of micro-computed tomographic imaging (Pasqualini et al. 2015). This study evaluated procedural errors in curved root canals and found that both instrumentation systems caused negligible procedural errors with minimal apical transportation. Pasqualini et al. (2015) evaluated the shaping properties of two glide path-shaping NiTi rotary systems: ProGlider/ProTaper NEXT (PG/PTN) and ScoutRaCe/Bio-RaCe (SR/BR). Specimens were scanned for matching volumes; surface areas and post-treatment analyses with the use of micro-CT. These researchers concluded that both SR/BR and PG/PTN shaping systems provided root canal preparation without significant shaping errors in maxillary first molar curved canals. The PG/PTN system, however, resulted in a more centered and less invasive preparation.

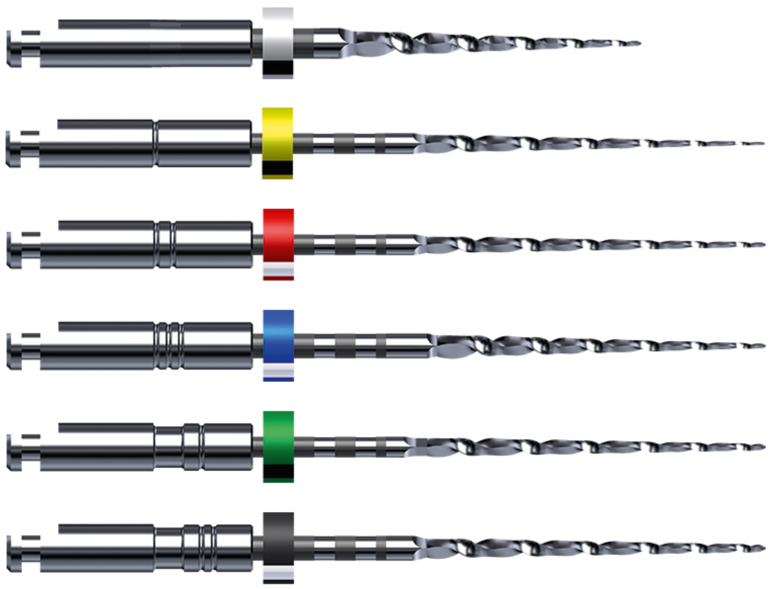

Figure 1.19: BioRaCe (FKG Dentaire) instruments from top to bottom – BR0 (white), BR1 (yellow), BR2 (red), BR3 (blue), BR4 (green), and BR5 (black)

1.4.2. OneShape (Micro-Mega)

OneShape (Micro-Mega) (Fig. 1.20) is a single-file NiTi rotary shaping system made of a conventional austenite 55-NiTi alloy and characterised by different cross-sectional designs over the entire length of the file.

This single-file instrumentation system is used in a full clockwise rotation. The cross section of the tip region has three cutting edges. The cross section of the middle region progressively changes from a three-cutting-edge design to two cutting edges, and the cross section of the shank is an S-shaped cross section with two cutting edges.

The asymmetric cross section geometry of the file generates traveling waves of motion along the active part of the file (Capar et al. 2014). The OneShape instrument has a tip size of 25, a constant taper of 6%, and is characterized by different cross-sectional designs over the entire length of the working part (Bürklein, Benten and Schäfer, 2013).

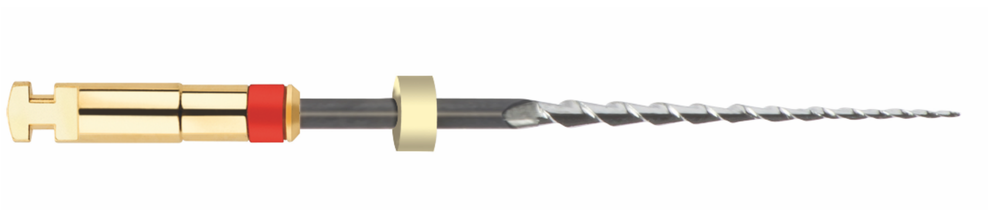

Figure 1.20: OneShape single file NiTi rotary file

A 2015 study compared the amount of apically extruded bacteria following the use of OneShape-, PTN- and Twisted File (TF) (TF; SybronEndo, Orange, CA) systems (Türker, Uzunoğlu and Aslan, 2015). The study concluded that all instrumentation systems extruded bacteria beyond the foramen but that the OneShape system extruded fewer bacteria compared to the TF- and PTN systems.

Results of Bürklein, Benten and Schäfer's 2013 study were that OneShape decreased the preparation time by 59% compared with Mtwo (VDW, Munich, Germany), a full-sequence rotary NiTi system. A concern raised here and in earlier studies was the associated decrease in irrigation time and subsequent chemical debridement of the root canal system. As a result, these authors recommended increased volumes of irrigation solutions in addition to irrigant activation for improved chemical dissolution of residual debris and disinfection of the root canal system. This study by Bürklein, Benten and Schäfer examined canal straightening, as well as preparation time. The results for all the instruments were comparable to those of other investigations carried out under similar experimental conditions (Bürklein and Schäfer, 2006; Bürklein et al. 2012). The mean straightening value for OneShape was 1.74° and for Reciproc – a single-file reciprocating system – was 1.35°.

A study evaluating canal straightening and apical transportation between OneShape-, WaveOne- and Reciproc instruments showed significantly less canal straightening and apical transportation in the WaveOne and Reciproc groups. These researchers attributed the results to the flexibility of the instruments in these two groups, which stems from its M-Wire construction (Saber, Nagy and Schäfer, 2015).

Pereira et al. (2013) have shown that the physical and mechanical properties of M-Wire renders root canal instruments more flexible and more fatigue resistant than those made from conventional austenitic NiTi, like OneShape. According to these researchers, another feature that contributed to these results was the use of WaveOne and Reciproc in a reciprocating motion as opposed to the continuous rotation of OneShape. Several studies have claimed that this working motion is associated with well-centered preparations and reduced procedural errors (Varela-Patiño et al. 2010; Franco et al. 2011).

Furthermore, this reciprocating motion extends the lifespan of instruments in comparison with continuous rotation (De-Deus et al. 2010; You et al. 2010). OneShape, however, prepared the root canals significantly faster than Reciproc and WaveOne did. All the file systems in the study by Pereira et al. (2011) successfully maintained the original curvature of severely curved canals in extracted teeth. These results are in accordance with those found in other studies (Bürklein et al. 2012; You and Cho, 2012; Marzouk and Ghoneim, 2013; Capar et al. 2014).

1.4.3. ProTaper Gold (Dentsply Sirona)

ProTaper Gold instruments (PTG) (Dentsply Sirona) (Fig. 1.21) are newly introduced endodontic instruments with the same geometries as ProTaper Universal instruments (PTU) (Dentsply Sirona). The manufacturer claims that these instruments present enhanced mechanical properties because of their innovative metallurgy, which exhibits two-stage specific transformation behaviour and high Af temperatures (Hieawy et al. 2015).

Like PTU, PTG instruments each demonstrate a convex triangular cross section and have a continuously changing helical angle. Each instrument falls into one of two categories: shaping instruments (SX, S1, S2) and finishing files (F1, F2, F3, F4, F5). Although shaping instruments demonstrate progressively tapered design, finishing instruments have fixed tapers between D1 and D3, and their tapers decrease progressively from D4 to D14 (Ruddle, 2005). The study by Hieawy et al. (2015) examined phase transformation behaviour and resistance to bending and cyclic fatigue of PTG and PTU. ProTaper Gold files were found to be significantly more flexible and resistant to fatigue than PTU files. The fatigue life of size S1 and S2 was significantly longer than that of sizes F1 to F3 files. Apart from demonstrating two-stage transformation behaviour, the study found that Af temperature of PTG instruments (50.1°C ± 1.7°C) was higher than that of PTU instruments (21.2°C ± 1.9°C).

Figure 1.21: ProTaper Gold instruments (Dentsply Sirona) – Sx (top), S1 (purple), S2 (white), F1 (single striped yellow), F2 (red), F3 (blue), F4 (black), and F5 (bottom)

Like PTU, PTG instruments each demonstrate a convex triangular cross section and have a continuously changing helical angle. Each instrument falls into one of two categories: shaping instruments (SX, S1, S2) and finishing files (F1, F2, F3, F4, F5). Although shaping instruments demonstrate progressively tapered design, finishing instruments have fixed tapers between D1 and D3, and their tapers decrease progressively from D4 to D14 (Ruddle, 2005). The study by Hieawy et al. (2015) examined phase transformation behaviour and resistance to bending and cyclic fatigue of PTG and PTU. ProTaper Gold files were found to be significantly more flexible and resistant to fatigue than PTU files. The fatigue life of size S1 and S2 was significantly longer than that of sizes F1 to F3 files. Apart from demonstrating two-stage transformation behaviour, the study found that Af temperature of PTG instruments (50.1°C ± 1.7°C) was higher than that of PTU instruments (21.2°C ± 1.9°C).

A recent study evaluated the cyclic fatigue and torsional resistance of Hyflex EDM files (Coltene/Whaledent, Altstätten, Switzerland), PTG instruments and PTU instruments through the use of a stainless steel block with 1.5-mm diameter and 3-mm radius of a 60° angle of curvature (Kaval and Capar, 2017). In this study, Hyflex EDM files demonstrated significantly higher resistance to cyclic fatigue than could be explained by its controlled M-Wire construction, which allows well-controlled- and non-contact shaping of the files and could improve their mechanical properties. ProTaper Universal instruments presented lower cyclic fatigue and torsional resistance than PTG instruments in spite of their similar design. These results were in accordance with those presented by Elnaghy and Elsaka (2016c) who also attributed the results to the metallurgy of PTG. A separate study comparing the flexibility and cyclic fatigue resistance of PTG and PTU showed that PTG files were significantly more flexible and resistant to fatigue than PTU files.

ProTaper Gold instruments and PTU exhibited dissimilar phase transformation behaviour, which may be attributed to the special heat treatment history of

PTG instruments. These researchers concluded that PTG might be more suited for preparing canals with more abrupt curvatures (Hieawy et al. 2015).

A study examining canal transportation in simulated curved canals prepared with PTU and PTG showed that these two systems produced similar canal transportation in the straight part of the canal (Silva et al. 2016). In the curved part, however, Silva et al. found that the PTG system produced overall less canal transportation when compared to the PTU system. This finding contrasts with a study that showed PTG and PTU as having similar root canal shaping abilities in the preparation of mesial canals of mandibular first molars (Elnaghy and Elsaka, 2016b). It is important to note that the former study examined colour stereomicroscopic images after shaping resin blocks while the latter used CBCT images.

1.4.4. ProTaper NEXT (Denstply Sirona)

The ProTaper NEXT (Denstply Sirona) rotary shaping system is reported to deliver the same predictable results as its predecessor PTU (Denstply Sirona), but reportedly with greater efficiency and with fewer files. There are five instruments in the system but, according to the manufacturer, most canals can be prepared with the use of the first two only. The system comprises X1 (17.04), X2 (25.06), X3 (30.07), X4 (40.06), and X5 (50.06), which are all characterised by a rotational phenomenon known as “precession” or “swagger” (Fig. 1.22).

This innovative off-centered rectangular cross section is claimed to give the files a snakelike swaggering movement as they advance into the root canal (Scianamblo, 2011) (Fig. 1.23 a and b). ProTaper NEXT features a bilateral symmetrical rectangular cross section with an offset from the central axis of rotation, except in the last 3 mm of the instrument (D0 –D3). The exception is ProTaper X1, which has a square cross section in the last 3 mm to give the instruments a little more core strength in the narrow apical part. The shorter handle of PTN also allows for improved accessibility to teeth and the file’s M-

Wire NiTi construction makes it almost 400% more resistant to cyclic fatigue. This level of resistance decreases the potential for broken instruments, and increases flexibility (Gagliardi et al. 2015).

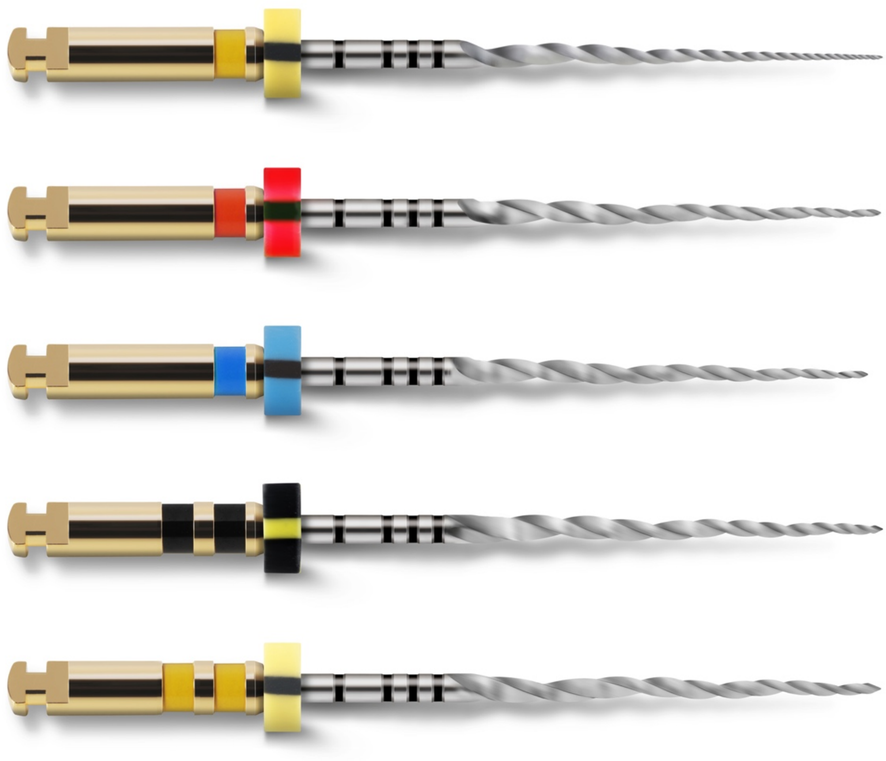

Figure 1.22: ProTaper NEXT files (Dentsply Sirona) - X1 (top), X2 (red), X3 (blue), X4 (black) and X5 (bottom)

According to Van der Vyver and Scianamblo (2013) the benefits of the PTN design include:

1. Further reduction in the engagement between the instrument and the dentine walls, which contributes to a reduction in taper lock, screw-in effect, and stress on the file;
2. Removal of debris in a coronal direction because of the off-centre cross section allowing for more space around the flutes of the instrument and leading to improved cutting efficiency through continuous contact of the blades with the surrounding dentine walls;

3. The swaggering motion of the instrument initiating activation of the irrigation solution during canal preparation and improving debris removal;
4. Reduced risk of fracture through less stress on the file and more efficient debris removal;
5. Each instrument's ability to cut a larger envelope of motion (larger canal preparation size) compared to a similarly sized instrument with a symmetrical mass and axis of rotation, which allows the clinician to use fewer instruments to prepare a root canal to adequate shape and taper to allow for optimal irrigation and obturation; and
6. A smooth transition between instruments because of a design that ensures that the instrument sequence itself expands exponentially.

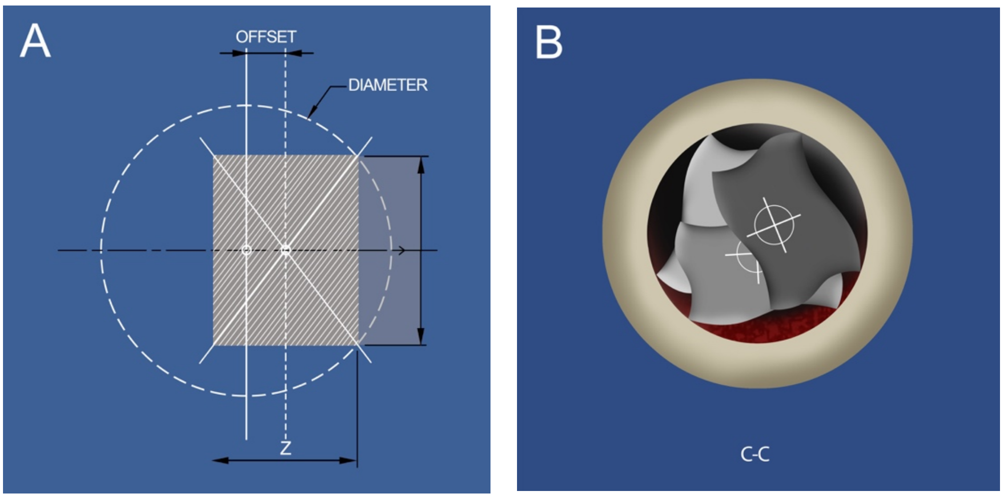

Figure 1.23: Schematic representation of (a) an off-set rectangular file demonstrating the adjustability of the distance of the offset from central axis; (b) rectangular offset cross section of ProTaper NEXT showing two points of contact with the dentine wall as the file rotates (Courtesy of Dr. M Scianamblo, San Rafael, California)

A study of curved canals by Pasqualini et al. (2015) that compared PTN to the BioRaCe system (BR) (FKG, Dentaire) demonstrated that PTN resulted in a more centered and less invasive preparation than that obtained with the BR system. This study showed no significant differences in post-instrumentation volumes and surface areas between the two groups. However, at a level 1 mm from the canal apex and at the point of maximum curvature lower canal transportation scores were recorded for PTN used after glide path enlargement than for the PG instrument than BR used after glide path enlargement with ScoutRaCe (FKG Dentaire). Centrifugal increase in canal diameters between the two groups was similar and PG/PTN demonstrated a more conservative increase of canal areas and a reduction of the inner dentinal wall thickness at the point of maximum curvature. The same study also analysed the final canal taper after shaping with PTN X2 in 3D. Results showed a homogeneous increase in canal taper, ranging from 6% to 7%, which was consistent with the declared taper of the instrument profile.

A study by Da Silva Limoeiro et al. (2016) demonstrated the inability of NiTi systems to completely shape root canal walls. The authors showed that following instrumentation with BR, 11.42% of the surfaces were untouched, and 15.46% of the walls remained unprepared after the use of PTN. These values are in line with those reported by Busquim et al. (2015) in which files left 9% to 16% of the walls untouched and with those reported by Gagliardi et al. (2015) who found a 6% to 13% mean range of untouched areas. The Gagliardi et al. (2015) study evaluated the shaping characteristics of PTG, PTN, and PTU in curved canals, and showed that the first and last of these produced significantly less transportation than PTN and maintained more dentine than PTU. PTN, however, displayed less canal wall contact than both PTG and PTU.

In a study that evaluated the frequency of dentinal micro-cracks after root canal preparation with PTN- and TFA (SybronEndo) systems through micro–computed tomography. Results showed that root canal preparation with the two systems did not induce the formation of new dentinal micro-cracks (De-Deus et al. 2015).

1.4.5. TRUShape 3D Conforming Files (Dentsply Sirona)

TRUShape 3D Conforming Files (TRS) (Dentsply Tulsa Dental Specialties, Tulsa, OK, USA) (Fig. 1.24) were launched in 2015 in four available sizes (20, 25, 30, 40), each with a variable regressive 6% taper to a maximum flute diameter of 0.80 mm. All instruments have the same symmetric triangular cross section and exhibit an S-curve shape resulting in a variable overall taper of the instrument.

The cutting part of these instruments is made of heat-treated NiTi alloy with proprietary processing. The heat treatment is applied after flutes are ground into blanks from commercially available nickel titanium to shape set a file into characteristic bends (Ammon et al. 2014). The unique S-shape of the TRS files creates an innovative envelope of motion within the canal that conforms to unconstrained spaces while respecting constrained spaces. This shape allows the files to adapt to areas of the canal greater than the nominal instrument size. TRUShape 3D Conforming Files are claimed to preserve more dentinal structure when they are used to prepare the entire root canal (Dentsply Tulsa Dental Specialties, 2015a; Elnaghy and Elsaka, 2016d).

TRUShape 3D Conforming Files are reported as allowing for a predictable apical shape while producing up to 32% less apical transportation than conventional ISO prepared canals. The TRS instruments are also reported to reduce bacteria loads from root canal walls more than Twisted Files do (SybronEndo) in the absence of antimicrobial irrigant (Bortoluzzi et al. 2015).

Figure 1.24: TRUShape 3D Conforming Files (Dentsply Tulsa Dental Specialties)

1.5. Reciprocating Root Canal Shaping Systems

Nickel titanium instruments used in a reciprocation motion were recently introduced for endodontic shaping. Reciprocating NiTi files differ from NiTi files that use continuous rotation by working in a similar but reverse "balanced force" action and using a pre-programmed motor to move the files in a back and forth "reciprocal motion" (Webber et al. 2011). A significant setback of the NiTi instruments used in rotation has been the fracture rate of these files, which has been attributed to their use in continuous rotation (Walia, Brantley and Gerstein, 1988; Parashos and Messer, 2006). There are claims that reciprocating endodontic instruments are more resistant to instrument separation, allow for easier treatment and, ultimately, shorten the learning curve for NiTi file systems (Grande et al. 2015).

The reciprocating working motion consists of a cutting direction that is counter-clockwise (CCW) and a reverse direction that is clockwise (CW). The fact that the angle of the CCW cutting direction is greater than the angle of the reverse direction is alleged to ensure that the instrument continuously progresses towards the terminus of the root canal (Bürklein, Benten and Schäfer, 2013).

The claim that reciprocating endodontic instruments are more resistant to instrument separation can be explained by the endurance limit. The endurance limit is defined as the level of torsional stress or strain at which a file can be subjected to virtual infinite cycles without failure where a cycle is intended as a loading stress or strain and releasing (Lindeburg, 1999). This value will be a specific deflection angle characteristic of each instrument and it will depend on the size and design features (Lindeburg, 1999). Virtually each time that a file is cutting dentine in rotation and is constricted inside the canal, there is a certain degree of torsional deformation that develops on its axis. If this deformation is maintained under the limits of the plastic deformation, there will be no structural changes. However, if this repeated cyclic axial deformation is accrued and exceeds the endurance limit, the metal will fracture because of torsional fatigue. This mechanism of stress is added to the flexural fatigue that is developed within a curved root canal (Pedullà et al. 2015). The idea of limiting the angle of rotation in the cutting verse under the endurance limit of the instruments led to the development of the reciprocating movement. The aim was to create a motion with a rotary effect in which the angle of rotation in the cutting verse is higher than the angle of rotation in the opposite noncutting verse. This determines the final rotation of the instrument that will perform a complete turn for a certain number of reciprocating cycles (Grande et al. 2015).

Stainless steel files have been used in a similar motion during glide path enlargement. Studies have demonstrated that NiTi reciprocating instruments decrease preparation time, increase cyclic fatigue life, and have a shaping ability similar to that of systems that use continuous rotation (Berutti et al. 2012a; De-Deus et al. 2013; Robinson et al. 2013). Incidences of reciprocating instrument deformation and fracture of instruments are fewer than those reported for rotary instruments (Sanches Cunha et al. 2014; Plotino, Grande and Porciani, 2015). Another reported advantage of using reciprocating endodontic systems is that unlike conventional rotary systems that utilise a series of instruments for shaping, reciprocating systems like WaveOne (Dentsply Sirona) and Reciproc (VDW) are able to shape canals with the use of one instrument only in some cases (Do-Amaral et al. 2016). Significantly fewer incidences of instrument separation and deformations of reciprocating files have been reported (Sanches Cunha et al. 2014; Plotino, Grande and Porciani, 2015).

Studies comparing the fracture risk of conventional rotating files and reciprocating instruments showed a significantly higher number of fractures in the rotating file group (Varela-Patiño et al. 2008; Varela-Patiño et al. 2010). Further reports show that file deformation and life span are not influenced by operator experience or the establishment of a mechanical glide path (Saleh et al. 2013; Generali et al. 2014; Türker et al. 2014). Wan et al. (2011) claim that reciprocating files undergo decreased stress and should therefore have a greater fatigue resistance because reciprocating files travel shorter circumferential distances than do rotary files. Various studies have concluded that the reciprocating motion extends the life span of NiTi endodontic files (Pedullà et al. 2013; Pérez-Higueras, Arias, and De la Macorra, 2013; Vadhana et al. 2014).

1.5.1. Properties of Reciprocating Root Canal Shaping Systems

1.5.1.1. Cyclic Fatigue and Bending Resistance

The amplitude of reciprocation has been shown to influence the cyclic fatigue life of reciprocating files. Increased angles of reciprocation with subsequent increases in the angle of progression for each reciprocation cycle reportedly reduces the resistance to cyclic fatigue (Gambarini et al. 2012; Saber Sel and Abu El Sadat, 2013). A study by Shin et al. (2014) reported that the fatigue life is reduced when the reciprocating amplitude increases in stationary reciprocation and is increased by 50% to 355% more than is the case with conventional rotating files. The results for progressive reciprocating files are even higher; they exhibit a fatigue life enhancement of up to 990% beyond the fatigue life of conventional rotating files. During progressive reciprocating motion, the most critically strained locations move forward to new locations as the file advances, distributing fatigue damage to various points on the circumference.

1.5.1.2. Cutting Efficiency

Studies examining the cutting efficiency of Reciproc, Twisted File (TF) Adaptive (SybronEndo, Orange, CA) in both reciprocating files and conventional rotating files showed no significant difference in the cutting ability between the two types of movement (Giansiracusa Rubini et al. 2014; Gambarini et al. 2016). There are, however, only a few studies investigating the cutting efficiency of the new reciprocating files. Results of studies by Plotino et al. (2014) and Tocci et al. (2015) revealed that Reciproc and TF Adaptive exhibited significantly higher cutting efficiency than WaveOne. Another study by Gambarini et al. (2016) showed that the cutting ability was not reduced by prolonged clinical use. A combination of the two movements has proved successful.

Conventional rotating files used during glide path enlargement and shaping with reciprocating files have produced centered preparations. Berutti et al. (2012b) found that endodontic preparation with the Primary WaveOne file following glide path enlargement with the PathFile system produced a preparation that was more centered.

1.5.1.3. Other Reported Advantages

Two studies compared the extrusion of debris during retreatment procedures rotary files and reciprocating files and the results showed that reciprocating files are associated with less debris extrusion compared to rotary files (Silva et al. 2014; Dincer, Er and Canakci, 2015). Reciprocating files are effective in removing the root canal filling material in less time compared with rotary files. These files also seem to cause fewer or an equivalent rate of dentine micro-cracks compared with rotary full-sequence systems (Plotino et al. 2015). A study by Alattar, Nehme and Diemer (2015) demonstrated that increasing the number of brushing strokes creates increased dentinal cutting in the direction of those strokes.

1.5.2 WaveOne (Dentsply Sirona)

In 2011, the WaveOne NiTi files system (Dentsply Sirona) (Fig.1.25) was launched as a single-use single-file system to shape the root canal in a reciprocating motion. The system is constructed of M-Wire and is made up of three files. The WaveOne Primary (25/08) and WaveOne Large (40/08) files have fixed tapers of 8% from D1-D3, whereas from D4-D16, they demonstrate a progressively decreasing percentage tapered design (Ruddle, 2012).

The WaveOne Primary file is used to prepare the majority of root canals with a secured glide path preparation. The WaveOne Large file is mainly indicated for larger diameter and relatively straight root canal systems (Webber et al. 2011).

The WaveOne Small file (21/06) has a fixed taper of 6% over its active portion and is mainly used when the Primary WaveOne file will not progress in canals with a smooth reproducible glide path. It is mainly designed to work in smaller diameter, longer length, and more apically curved root canals (Ruddle, 2012).

The rationale behind the use of a single Primary WaveOne instrument (25/08) began with the assumption of Buchanan (2000) when he defined the ideal diameter for the final instrument used for curved root canals as ISO sizes 20 or 25.

Figure 1.25: WaveOne system (Dentsply Sirona)

Each of the WaveOne instruments exhibits a modified convex triangular cross section at the tip end and a convex triangular cross section at the coronal end, which improves overall instrument flexibility. The convex triangular section is modified with a radial land at thte tip and presents a cutting angle projected to the left that differentiates it from continuous rotation systems (Do-Amaral et al. 2016). The variable pitch flutes along the length of the instrument are said to considerably improve safe use of these files.

The WaveOne instruments are used in a modified CW/CCW movement. These instruments are used with different angles in cutting and noncutting verses in a partial reciprocation motion of 170°/50° with an average speed of 350 rpm (Grande et al. 2015).

1.5.3. WaveOne Gold (Dentsply Sirona)

The conventional WaveOne system was manufactured from M-Wire technology. WaveOne Gold instruments are manufactured with the use of a post-manufacturing thermal process during which a new phase-transition point between martensite and austenite is identified to produce a file with super-elastic NiTi metal properties. This process gives the file a gold finish and improves mechanical characteristics. The properties of gold wire have been previously discussed in this chapter.

The WaveOne Gold Primary file is 50% more resistant to cyclic fatigue, 80% more flexible and 23% more efficient than the conventional WaveOne Primary instrument (Webber, 2015; Ruddle, 2016). Owing to the super-elastic properties of the new gold metal, the file may appear slightly curved when it is removed from a curved root canal because the metal demonstrates less memory compared to conventional NiTi or M-Wire (Fig.1.26).

The file can either be straightened out or if it is placed back into a root canal it will follow the natural shape of that canal (Webber, 2015). Another advantage of this reduced memory of the file is that in cases with difficult straight-line access it is possible to slightly pre-curve the file to allow easy placement into the canal orifices.

Figure 1.26: WaveOne Gold files may appear slightly curved when it is removed from a curved root canal because the metal demonstrates less memory

Conventional WaveOne instruments are characterised by different cross-sectional designs over the entire length of the working part of the instruments. The WaveOne Gold file exhibits a unique alternating off-centered parallelogram-shaped cross-section design with two 85-degree cutting edges (Fig. 1.27) (Webber, 2015).

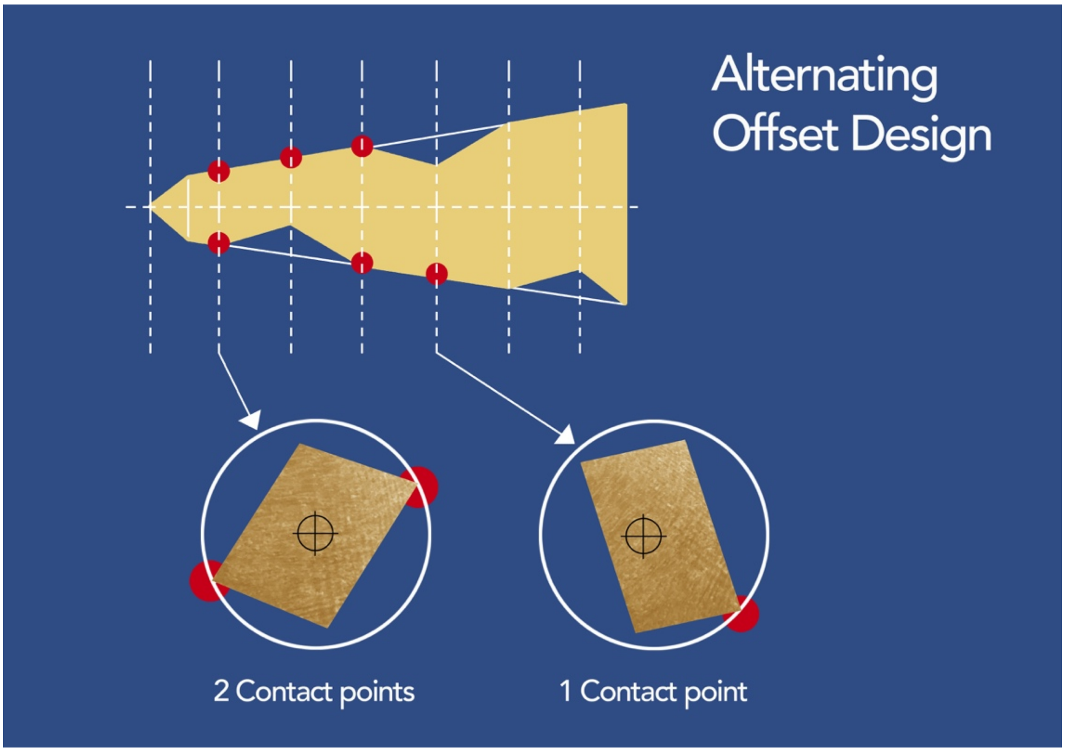

Figure 1.27: Schematic representation illustrating the alternating off-centered parallelogram-shaped cross-section design with two 85-degree cutting edges. The design limits engagement between the file and dentine to only one or two points of contact at any given cross section (Adapted from Ruddle, 2016)

According to Ruddle (2016) this design limits the engagement between the file and the dentine to only one or two contact points at any given cross section. This reduces taper-lock and the screw-effect, improves safety, increases cutting efficiency, and provides more chip space to auger debris coronally, in comparison with its predecessor WaveOne. The newly designed files are also manufactured with an ogival, roundly tapered and semi-active guiding tip to ensure that the file progress safely along canals with a secured and confirmed reproducible glide path (Webber, 2015; Ruddle, 2016).

The WaveOne Gold single-file reciprocating system is available in four different file tip sizes in lengths of 21 mm, 25 mm, and 31 mm:

1. **WaveOne Gold Small File** (yellow ring) (Fig. 1.28) with tip of the file size ISO 20 and the first 3 mm of the file (D1-D3) having a continuous taper of 7%.

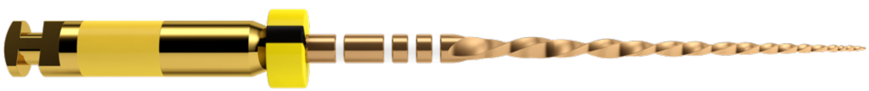

Figure 1.28: WaveOne Gold Small File (20/07)

2. **WaveOne Gold Primary File** (red ring) (Fig. 1.29) with tip of the file size ISO 25 and the first 3 mm of the file (D1-D3) having a continuous taper of 7%.

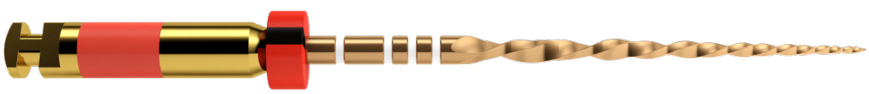

Figure 1.29: WaveOne Gold Primary File (25/07)

3. **WaveOne Gold Medium File** (green ring) (Fig. 1.30) with tip of the file ISO 35 and the first 3 mm of the file (D1-D3) having a continuous taper of 6%.

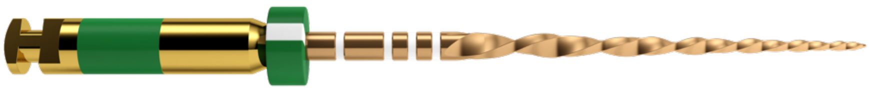

Figure 1.30: WaveOne Gold Medium File (35/06)

4. **WaveOne Gold Large File** (white ring) (Fig.1.31) with tip of the file ISO 45 and the first 3 mm of the file (D1-D3) having a continuous taper of 5%.

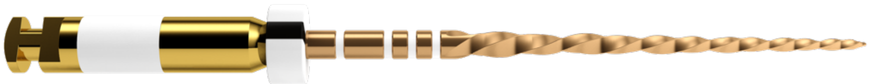

Figure 1.31: WaveOne Gold Large File (45/05)

From D4-D16 each file demonstrates a progressively decreasing-percentage tapered design to ensure more flexibility and to preserve more dentine in the body of the prepared root canal to ensure more conservative root canal preparations (Webber, 2015; Ruddle, 2016).

The WaveOne GOLD files also have shortened 11 mm handles that improve straight-line access into the posterior region of the mouth. They are colour-coded (according to ISO size) with an expanding ABS ring after autoclaving to promote the philosophy of single use (Webber, 2015).

All the abovementioned features produce a file system with improved mechanical and clinical benefits to ensure predictable root canal preparation.

In the majority of cases a single file can be used to complete root canal preparation with adequate resistance form to ensure exchange of irrigation solutions for adequate disinfection prior to root canal obturation in single- or multiple-root canal systems. According to the manufacturer, the Primary 25/07 file is usually the only file needed to fully shape almost any given canal. The semi-active guiding tip of the file is said to enable its progression along canals that have undergone glide path enlargement (Ruddle, 2016).

The WaveOne Gold CCW engaging angle is 150 degrees, while the CW disengaging angle is 30^{o}. After three CCW/CW cutting cycles the file rotates one full circle. According to Ruddle (2016) there are three major clinical advantages to WaveOne Gold's unique movement: (1) compared to continuous rotation, there is improved safety, as the CCW engaging angle is designed to be less than the elastic limit of each file; (2) in contrast with equal CW/CCW angles, unequal CW/CCW angles enable a file to more readily advance toward the desired working length without the use of excessive and potentially dangerous inward pressure; (3) compared to equal CW/CCW angles, unequal angles strategically enhance auguring debris out of the canal.

1.5.4. Reciproc Blue (VDW)

Over the last few years, Reciproc (VDW) (Figure 1.32) and WaveOne (Dentsply Sirona) have been touted as the most commercially available systems with reciprocating motion for root canal preparation. In 2011 the Reciproc System was introduced to the market by VDW (Munich, Germany) as a single-file reciprocating system. The claim was made that root canals could be completely prepared with only one Reciproc instrument.

According to Bürklein et al. (2012) Reciproc allows for more rapid shaping than full-sequence rotary systems and is suitable for use in curved canal. Reciproc files have a tip diameter of 25 and a taper angle of 0.08. The tapers are fixed 3 mm from the apex of the files and decrease in the middle and coronal sections (Plotino et al. 2012). The Reciproc file is S-shaped with two cutting edges and its manufacture requires the use of M-Wire alloy (Elnaghy and Elsaka, 2015b).

Reciproc Blue (Fig. 1.32), based on its predecessor Reciproc, was recently launched by VDW (Munich, Germany). Blue NiTi is a newly developed alloy that is obtained through a proprietary-specific oxide surface layer thermo-mechanical manufacturing process. Like M-Wire and Gold, Blue NiTi is thermally treated NiTi designed to improve the mechanical properties of endodontic instruments such as fatigue resistance, flexibility, cutting efficiency, and canal centering ability (Lopes, et al. 2013; Pereira, Gomes et al. 2103). Thermal treatment modifications, in addition to the reciprocating motion, have already been shown to extend the life span of a NiTi instrument and its resistance to fatigue in comparison with continuous rotation movement (De-Deus et al. 2010; Pedullà et al. 2013).

Blue NiTi is produced after NiTi has undergone a complex heating-cooling proprietary treatment that results in a visible layer of titanium oxide in the surface of the instrument. This treatment controls the transition temperatures and creates a shape memory alloy, which is claimed by the manufacturer to result in superior mechanical properties and performance of the NiTi instruments (Hieawy et al. 2015; Silva et al. 2016).

Reciproc Blue is available in sizes 25 (with a taper of 8%), 40 (with a taper of 6%) and 50 with a taper of 5%. A recent study compared the bending resistance and cyclic fatigue of conventional Reciproc files to Reciproc Blue (De-Deus et al. 2017). The study concluded that the Blue thermally treated NiTi files showed overall improved performances when they were compared to conventional M-Wire super-elastic NiTi. Reciproc Blue demonstrated improved flexibility, fatigue resistance and reduced micro-hardness while at the same maintaining similar characteristics of the surface.

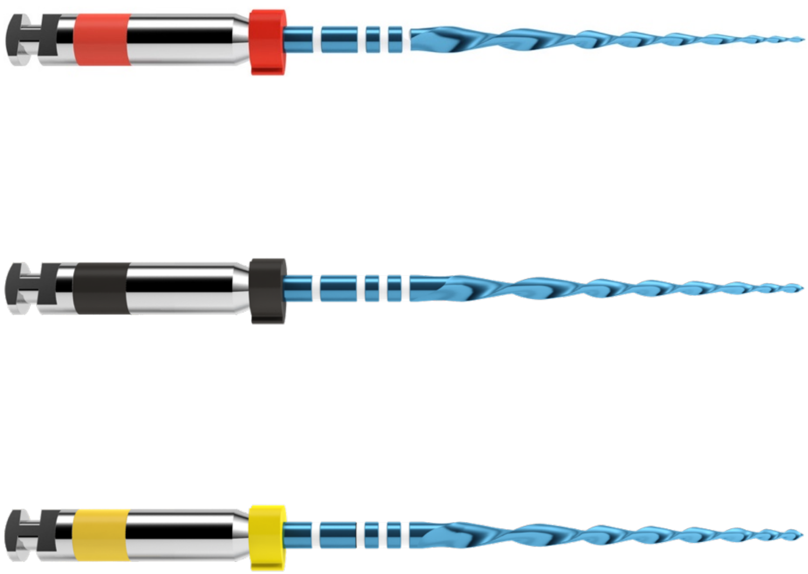

Figure 1.32: Reciproc Blue (VDW)– 25 (red), 40 (black) and 50 (yellow)

1.6. Micro-computed Tomography

New root canal study modalities like micro-CT allow researchers to view complex root canal systems in their entirety. The ideal shaping outcome is a canal that maintains its original anatomical shape following chemical debridement and removal of infected dentine.

Micro-computed tomography enables researchers to evaluate instrumentation techniques and shaping quality. This information is then used to raise the standard of clinical endodontic treatment. Various research tools have been used to study the intricacies of root canal systems. These include radiographs, the serial sectioning technique, computed tomography, and, more recently, X-ray micro-CT, more commonly referred to as micro-CT. Many of the morphological variations of canals cannot be viewed with conventional radiographs. The serial sectioning technique requires cutting of the teeth into sections and photographing them before instrumentation after which they are pieced back together, instrumented, separated and photographed again (Bramante, Berbert and Borges, 1987). This complicated technique can result in unknown tissue changes a loss of material, and resulting inaccuracies (Gambill, Alder and Del Rio, 1996).

Computed tomography (CT) offers researchers a three-dimensional view of root canals without any sectioning of samples, but is unable to identify subtle changes in root canal geometry after instrumentation (Dowker, Davis and Elliott, 1997). Micro-computed tomography effectively uses the same method as CT but can be performed on a smaller scale. Micro-computed tomography offers a superior resolution quality but can only be carried out on extracted teeth.

Micro-computed tomography scanners are based on cone-beam geometry and are optimised to obtain non-destructive high-resolution 3D imaging of small objects. This analytical tool permits detailed and non-destructive two-dimensional (2D) and 3D evaluation of root canal geometry and has enabled researchers to examine the effects of root canal instrumentation in three dimensions (Rhodes, Pitt Ford and Lynch, 2000; Paqué, Ganahl and Peters, 2009; Peters and Paqué, 2011).

Micro-computed tomography scans yield quantitative data that detail the performance of any given root canal shaping instrument. Newer machines offer resolutions in the micron range and can be accompanied by more accurate measurement software with the capabilities of matching multi-dimensional data from specimens before and after preparation (Peters, et al. 2003).

The spatial resolution of micro-CT has improved from 127 μm in the 1990s (Nielsen et al. 1995) to 11 μm over the last few years (Endal et al. 2011). A number of studies have used micro-CT based imaging to look at the effects of various instrumentation efficiencies and techniques (Pasqualini et al. 2012). Micro-computed tomography allows for the non-destructive analyses of variables such as volume, surface areas, cross-sectional shape, taper, canal transportation and the fraction of affected surface before and after instrumentation (Rhodes, Pitt Ford and Lynch, 2000). Details of the micro-CT scanning procedure, segmentation, and surface modelling have been described previously by Versümer, Hülsmann and Schäfers (2002).

The XTH 225 ST micro-focus X-ray tomography system (Nikon Metrology, Leuven, Belgium) (Fig. 1.33) is a micro-CT facility that consists of four separate functional units, a lead-lined cabinet, an external control module, an external chiller and computers. These computers have software that allow for the acquisition of X-rays, reconstruction of the X-rays into a 3D virtual image and visualisation and analysis of the image (Hoffman and De Beer, 2012).

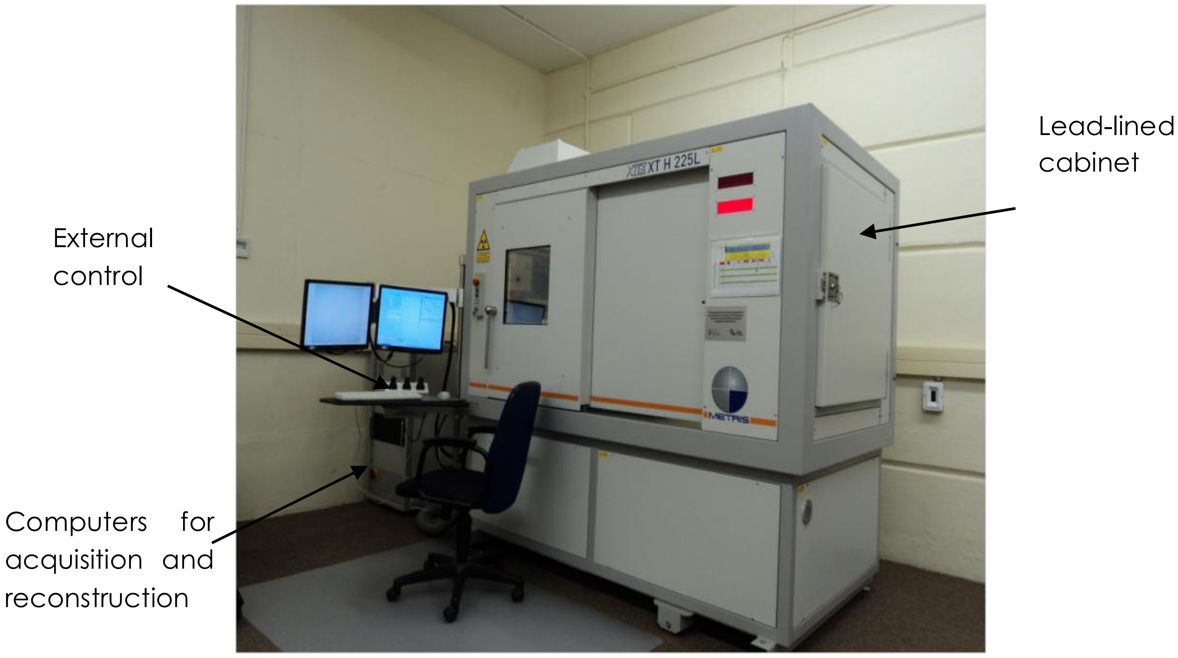

Figure 1.33: XTH 225 ST (Nikon Metrology, Leuven, Belgium)

This type of micro-focus X-ray system has an intrinsic 0.001-0.006 mm spatial resolution capability. The XTH 225 ST has a 5-axis sample manipulator that ensures stability of samples (weighing up to 50 kg) during scanning. The manipulator is installed in a lead-lined cabinet, is completely controlled by an acquisition computer, and can be adjusted to allow for horizontal optimisation to ensure maximum enlargement of the tooth for optimal spatial resolution. This adjustment ensures that samples are horizontally included in each 2D radiograph at all angles of rotation and for correct normalisation during the tomography reconstruction process (Fig. 1.34)(Hoffman and De Beer, 2012).

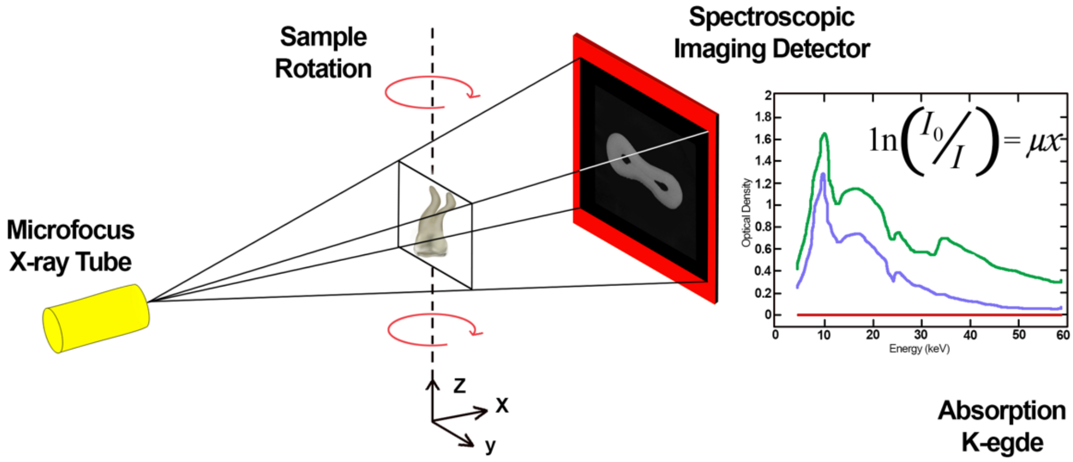

Figure 1.34: The tomographic process of the XTH 225 ST micro-CT system (Nikon Metrology, Leuven, Belgium)

A series of sequential 2D X-ray images is captured as the object is rotated through 360 degrees. These images are then reconstructed to generate a 3D volumetric representation of the object. The accurate rotation movement allows for up to 4000 or more 2D tiff-format projections that are reconstructed into a 3D volume. Reconstruction parameters are optimised automatically so that the quality of the scan is not dependent on the qualitative opinion of the operator. The final product from a reconstruction is a 3D volume file that can be directly imported in VGStudioMax visualization software (Volume Graphics GMBH, 2014).

Chapter 2: Aim and Objectives

2.1. Aim

The broad aim of this *ex-vivo* study was to determine with the use of micro-computed tomography scanning which of the glide path and root canal preparation technique combinations is best suited to the shaping of root canals after glide path preparation in curved mesio-buccal root canals of extracted human maxillary molars.

2.2. Objectives

The main objectives of this study were to:

1. Acquire 3D images of uninstrumented maxillary molars with curved canals via micro-CT scanning;

2. Enlarge glide paths in curved molar root canals using pre-curved stainless steel hand K-Files and two NiTi rotary glide path file systems, the One G and ProGlider files, and subsequently obtain 3D images via micro-computed tomography scanning;

3. Compare pre-instrumentation and post-instrumentation 3D images to assess the ability of the three glide path instrument groups to remain centered in the canal during glide path enlargement at levels 2 mm, 5 mm, and 9 mm from the apical foramen;

4. Compare pre-instrumentation and post-instrumentation 3D images of the three glide path instrument groups for transportation of the canal at levels 2 mm, 5 mm, and 9 mm from the apical foramen;

5. Shape curved molar root canals using OneShape, ProTaper NEXT and WaveOne Gold, and subsequently obtain 3D images via micro-computed tomography scanning;

6. Compare pre-instrumentation and post-instrumentation 3D images to assess the ability of the nine technique combination groups to remain centered in the canal after shaping and glide path enlargement at levels 2 mm, 5 mm, and 9 mm from the apical foramen;

7. Compare pre-instrumentation and post-instrumentation 3D images of the nine technique combination groups for transportation of the canal at a levels 2 mm, 5 mm, and 9 mm from the apical foramen; and

8. Compare the change in root canal volume between uninstrumented canals and canals after root canal shaping has been completed.

2.3. Hypothesis

The shaping techniques used after glide path preparation with pre-curved stainless steel K-Files will be less centered in the canal during shaping, will cause more apical canal transportation and will create smaller changes in root canal volume.

2.4. Statistical Null/Zero Hypotheses

There will be no differences (1) in canal centering ability and apical canal transportation values between pre-curved stainless steel K-Files, the ProGlider file and the One G file for the glide path preparation; (2) in canal centering ability, apical canal transportation values, and changes in root canal volume between the nine root canal preparation groups.

Chapter 3: Materials and Methods

3.1 Study Design

This *ex-vivo* study compared by means of micro-computed tomography physical changes within instrumented root canals of extracted maxillary molars. Study methods described by Hashem et al. (2012) and Elnaghy and Elsaka (2015a) were employed in this study.

3.2. Collection of Material

The teeth used for the purposes of this experiment were taken from a collection of adult teeth extracted for reasons unrelated to the objectives of this study. Teeth were collected from the outpatient oral surgery clinic of the University of Pretoria's Department of Maxillo-facial and Oral Surgery in its School of Dentistry (Faculty of Health Sciences). Permanent maxillary molars with curved mesial roots were chosen from a pool of extracted human teeth collected by dental students at the outpatient dental extraction clinic.

Each patient who attends this facility for dental extraction is asked to complete an informed consent form (Appendix A). Patients who give this written consent grant permission for their extracted teeth to be used for the purposes of scientific research. All donors were anonymized. Teeth are retained and distributed among researchers for research projects. Every aspect of the completed research project was conducted in line with the ethical and safety guidelines for handling human tissues and conducting laboratory research, as prescribed by South African law: The Health Professions Act 56 of 1974 (Health Professions Council of South Africa, 2008). The guidelines of the Faculty of Health Sciences' Research Ethics Committee were observed throughout the conducting of this study.

The extracted teeth were stored in labelled and sealed glass jars filled with saline at four degrees in a designated storage refrigerator. Directly after extraction, the teeth were rinsed under cold-running tap water for one minute. They were then placed in distilled water in a Clean50 ultrasonic water bath (Woson, Ningbo, China) for several cycles of 15 minutes each. Fresh distilled water was used for each new cycle and cycles were repeated until all evident soft tissue had been removed from the root surfaces. In order to avoid dehydration, the teeth were stored in glass jars filled with distilled water at four degrees Celsius. The teeth were disposed of following the completion of the research and the services of a medical waste company were used for this purpose. All the data collected was safely stored and will be saved for a minimum of 15 years from the commencement of this research.

3.3 Selection of teeth

Permanent maxillary first and second molars with curved mesio-buccal roots were chosen from the pool. The roots and apices of the selected molars were examined for defects and maturity using a Dental Operating Microscope (DOM) (Zumax Medical Co. Ltd, Suzhou, China) at 10x magnification (Fig. 3.1).

Figure 3.1: Dental Operating Microscope (DOM) (Zumax Medical)

3.3.1 Inclusion Criteria

Radiographs were taken to select 135 molars that fit the selection criteria using a digital radiography setup (RVG 6000 System, Eastman Kodak, Anaheim, CA, USA). Maxillary first and second molars with previously untreated and intact roots with closed apices were selected. Root canals with curvatures of 25 to 30 degrees as determined by the Schneider method (Fig. 3.2) were ultimately chosen (Schneider, 1971). Immature molars with wide root canals and open apices and canals were excluded from this study. An Endo-Access Bur (size 1) (Dentsply Sirona) was used to engrave the selected teeth with numbers from 1 to 135 for identification purposes.

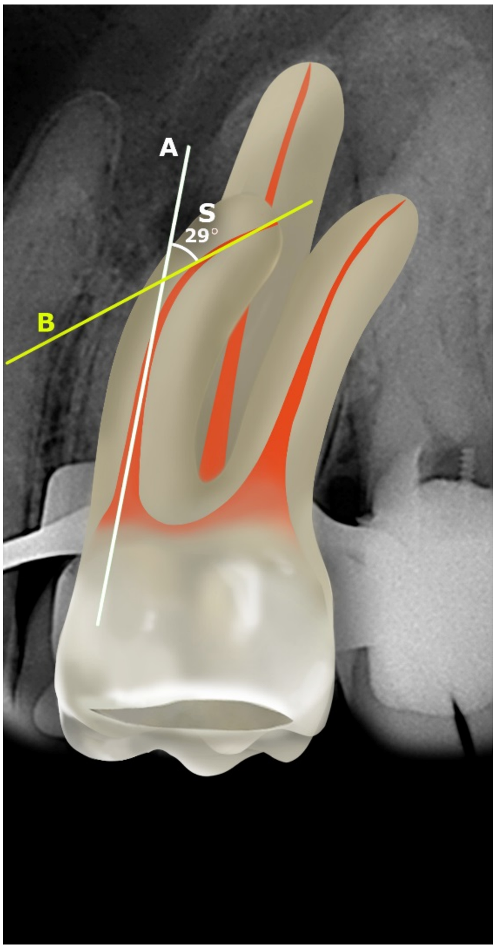

Figure 3.2: Schneider method for root curvature determination: a (straight line drawn along the coronal third of the canal); B (line drawn from the apical foramen to intersect the point where the first line left the long axis of the canal); S (Schneider angle)

3.3.2 Collection of Data

The selected teeth were mounted on a stable support and scanned before instrumentation (Scan 1) carried out by means of the XTH 225 ST micro-focus X-ray computed tomography system (Nikon Metrology, Leuven, Belgium) at the Micro-focus X-ray Radiography and Tomography facility (MIXRAD) at the South African Nuclear Energy Corporation (NECSA). Each tooth was set into a custom-made putty mould to facilitate mounting of the individual teeth onto the sample manipulator of the micro-focus x-ray cabinet. A series of sequential 2D X-ray images were captured as the object was rotated through 360°. These images were then reconstructed to generate a 3D volumetric representation of the object (Fig. 3.3).

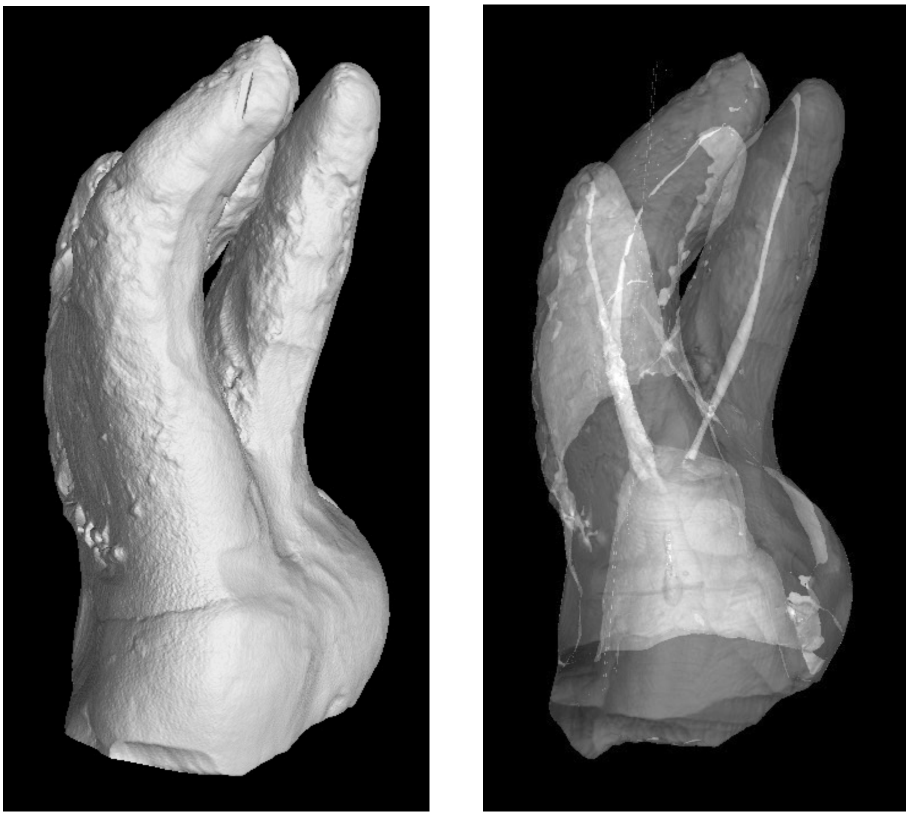

Figure 3.3: Pre-instrumentation scan: (a) three-dimensional view showing the root and crown morphology; (b) 80% transparency view revealing the root canal systems

Precise rotation movement allows for up to 4000 or more 2D tiff-format projections that are reconstructed into a 3D volume. Reconstruction parameters are optimised automatically so that the quality of the scan is not dependent on the qualitative opinion of the operator. The final product from a reconstruction is a 3D volume file that can be directly imported into VGStudioMax visualisation software (Volume Graphics GmbH, Heidelberg, Germany) (Volume Graphics GMBH, 2014). For this study, a total of 135 mesio-buccal root canals were selected in maxillary first and second molars, with either a single mesio-buccal- or two separate canals in the mesio-buccal roots. The teeth were randomly assigned into three equal groups of 45 canals each for glide path enlargement with the use of an online randomiser tool (Research Randomizer version 4.0 (Urbaniak and Plous, 2016).

3.4. Preparation of Teeth

The standard endodontic access was prepared and the curved canals that met the selection criteria were located and explored with a size 08 Senseus K-FlexoFile (Dentsply Sirona). A DOM (Zumax Medical) at 10x magnification was used for advancing passively into each canal until its tip was just visible at the apical foramen (Fig. 3.4).

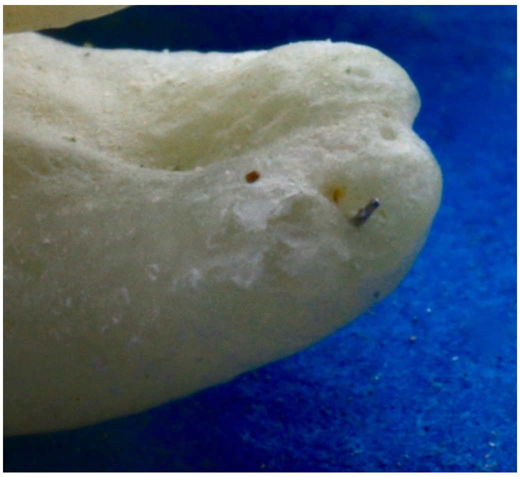

Figure 3.4: (a) A size 08 Senseus K-FlexoFile was advanced passively into each canal until its tip was just visible at 10x magnification at the apical foramen.

Working length was recorded by subtracting 0.5 mm from this measurement. Crowns of teeth were kept intact to reproduce clinical situations where the lack of straight-line access can cause unwanted directional tension or resistance during canal preparation (Hashem et al. 2012).

3.5. Glide Path Enlargement

A total of 135 root canals were prepared using the three glide path techniques. A group of 45 root canals was prepared with the use of manual glide path enlargement with pre-curved stainless steel size 10, 15, and 20 K-Flex files (Dentsply Sirona) to working length. Another 45 root canals were allocated to the One G group (Micro Mega) and the remaining 45 to the ProGlider group (Dentsply Sirona) for mechanical glide path enlargement. All the canals in the One G group (n = 45) were prepared with the One G instrument through use of the X-Smart Plus motor (Dentsply Sirona)(according to the manufacturer's instructions). The canals in the ProGlider group (n = 45) were enlarged by a single ProGlider file also used with the X-Smart Plus motor according to the manufacturer's instructions. RC Prep (Premier, Pennsylvania, USA) was used as a chelator in all canal preparations and 6% sodium hypochlorite (NaOCl) was used for canal irrigation after the use of each file. A new file was used for each tooth, and used files were observed for any signs of deformation and/or fracture. Access and glide path enlargement were carried out by a single operator.

3.5.1. Glide Path Enlargement using Pre-Curved Stainless Steel Senseus K-FlexoFiles

In each of the 45 canals, an initial reproducible glide path was prepared with the use of pre-curved size 10, 15 and 20 stainless steel Senseus K-FlexoFiles (Fig. 3.5). A final reproducible glide path to an ISO size 0.20 was confirmed when the stainless steel size 0.20 Senseus K-FlexoFile could be placed at working length, pulled backwards for 4 mm and pushed back with light finger pressure to full working length without interference or obstruction.

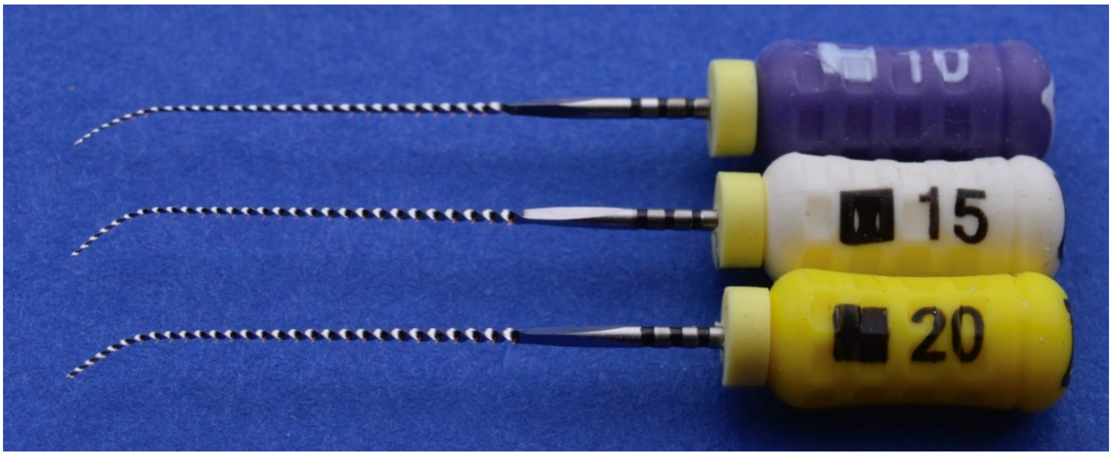

Figure 3.5: Pre-curved size 10, 15 and 20 stainless steel Senseus K-FlexoFile (Dentsply Sirona)

3.5.2. Glide Path Enlargement using One G

For each canal, a pre-curved stainless steel size 10 Senseus K-FlexoFile was negotiated to working length with increasing amplitudes of 1 to 3 mm to ensure an initial manually reproducible glide path. The X-Smart Plus motor was used with the One G (Micro Mega) according to the manufacturer's instructions for enlarging each canal in this group (n = 45) (Fig. 3.6).

Figure 3.6: One G (Micro Mega)

3.5.3. Glide Path Enlargement using ProGlider

The remaining 45 canals were assigned to the ProGlider (Dentsply Sirona) group. An initial manually reproducible glide path was first established in each canal with a pre-curved stainless steel size 10 Senseus K-FlexoFile. The K-File was negotiated to working length with increasing amplitudes of 1 to 3 mm after which a single ProGlider file (Dentsply Sirona) was used with the X-Smart Plus motor (Dentsply Sirona) according to the manufacturer's instructions (Fig. 3.7).

Figure 3.7: ProGlider (Dentsply Sirona)

After glide path preparation, all the canals were dried with paper points (ISO size 20) (Dentsply Sirona). The teeth were placed in the same custom moulds as for the pre-instrumentation scan (Scan 1) and scanned by the XTH 225 ST micro-focus X-ray computed tomography system to generate the glide path scan (Scan 2) for each tooth. VGStudioMax software enabled merging of the pre-instrumentation 3D images (Scan 1) and glide path preparation 3D images (Scan 2) for each tooth. Canals from Scan 2 were superimposed on corresponding canals from Scan 1 to measure the changes following glide path preparation (Fig. 3.8).

Figure 3.8: Glide path scan (Scan 2) superimposed on pre-instrumentation scan (Scan 1)

3.6. Root Canal Shaping

The specimens of each glide path group were randomly assigned to three equal groups of 15 canals each for root canal shaping with the same online randomiser tool as used for glide path enlargement (Urbaniak and Plous, 2016).

3.6.1 Group 1: Glide Path Preparation using Pre-curved Stainless Steel Senseus K-FlexoFiles and Shaping with OneShape (K/OS)

The canals in the OneShape group were prepared through the use of the OneShape instrument in the X-Smart Plus motor according to the manufacturer's instructions following glide path preparation with pre-curved K-Flex files (n =15) (Fig. 3.9).

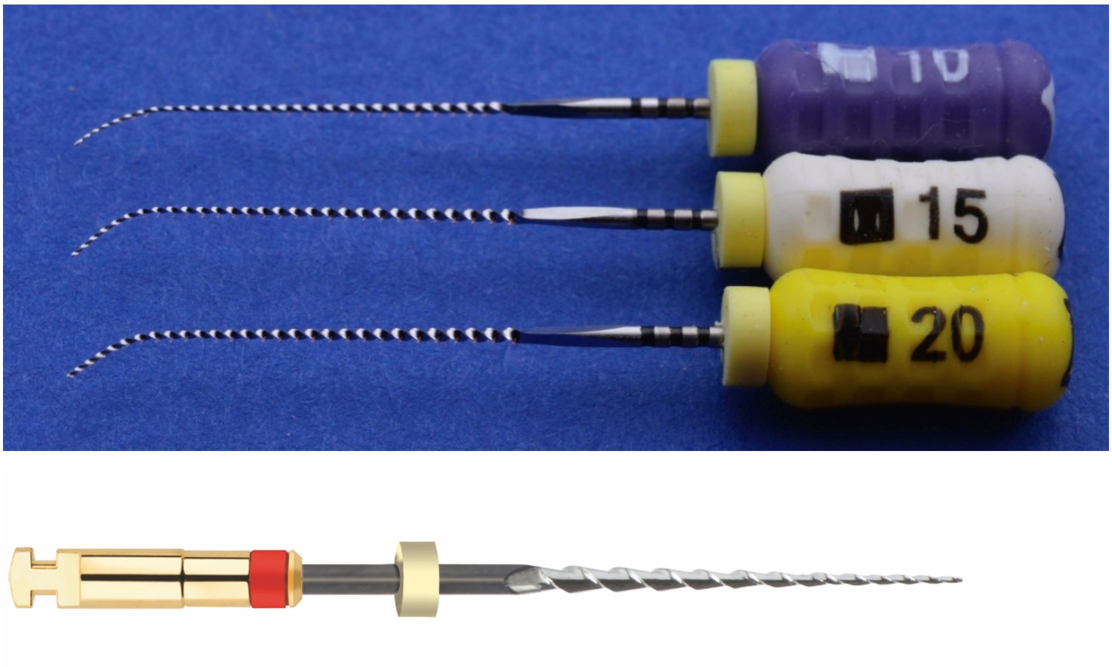

Figure 3.9: Pre-curved size 10, 15 and 20 stainless steel K-Flex files (Dentsply Sirona) and OneShape (Micro-Mega)

3.6.2 Group 2: Glide Path Preparation using Pre-curved Stainless Steel Senseus K-FlexoFiles and Shaping with ProTaper NEXT (K/PTN)

The canals in the ProTaper NEXT group were prepared with the use of X1 and X2 files in the X-Smart Plus motor according to the manufacturer's instructions after glide path preparation with pre-curved K-Flex files (n =15) (Fig. 3.10).

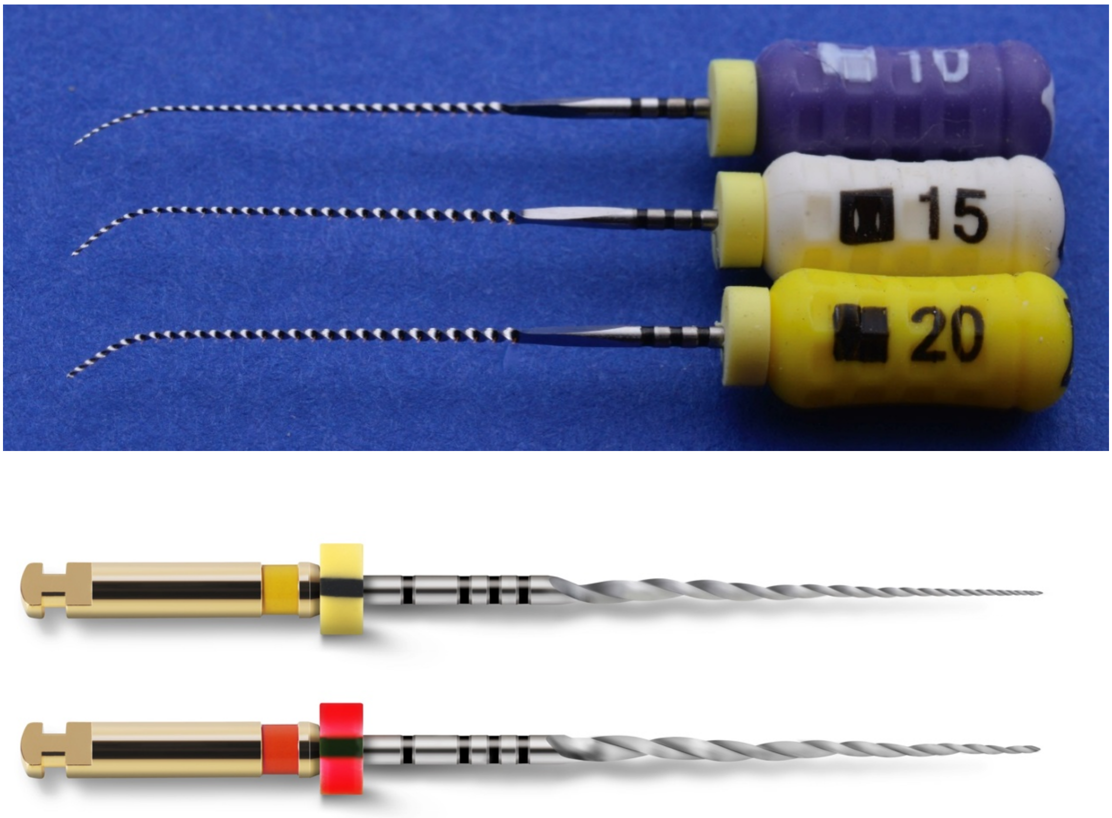

Figure 3.10: Pre-curved size 10, 15 and 20 stainless steel K-Flex files and ProTaper Next X1 and X2 (Dentsply Sirona)

3.6.3 Group 3: Glide Path Preparation using Pre-curved Stainless Steel Senseus K-FlexoFiles and Shaping with WaveOne Gold (K/WOG)

The canals in the WaveOne Gold group were prepared with the use of the primary file in the X-Smart Plus motor according to the manufacturer's instructions and following glide path preparation with pre-curved K-Flex files (n =15) (Fig. 3.11).

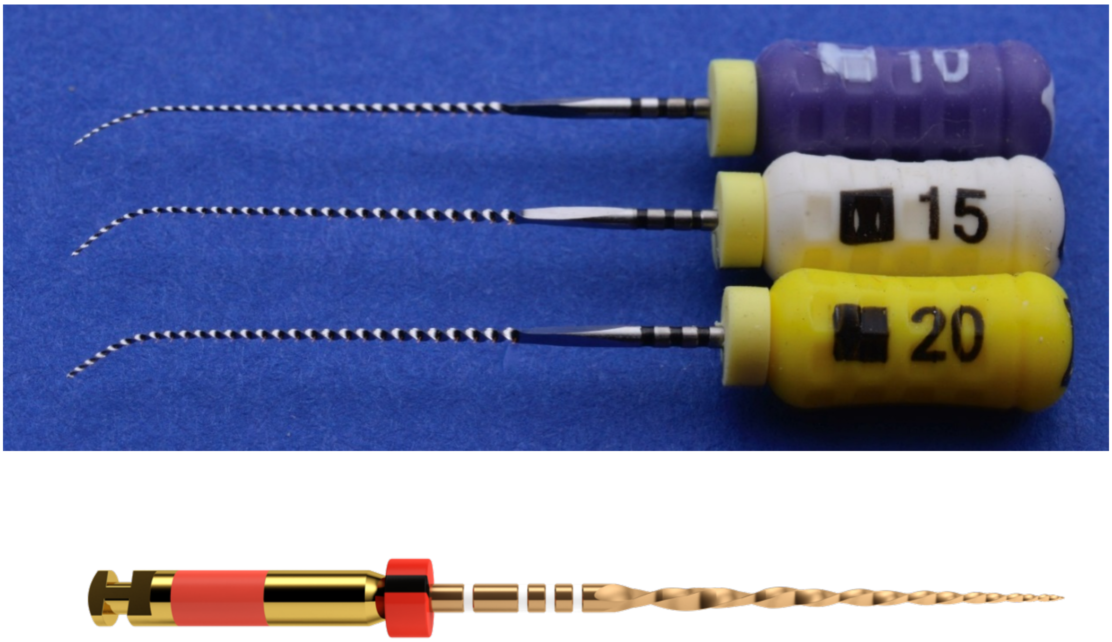

Figure 3.11: Pre-curved size 10, 15 and 20 stainless steel K-Flex files and Primary WaveOne Gold (Dentsply Sirona)

3.6.4 Group 4: Glide Path Enlargement with One G and Shaping with OneShape (OG/OS)

The canals in the OneShape group were prepared by use of the OneShape instrument in the X-Smart Plus motor after glide path enlargement with One G (n = 15), according to the manufacturer's instructions (Fig. 3.12).

Figure 3.12: One G and OneShape (Micro Mega)

3.6.5 Group 5: Glide Path Enlargement with One G and Shaping with ProTaper NEXT (OG/PTN)

The canals in the ProTaper NEXT group were prepared by using X1 and X2 files in the X-Smart Plus motor after glide path enlargement with One G (n =15), according to the manufacturer's instructions (Fig. 3.13).

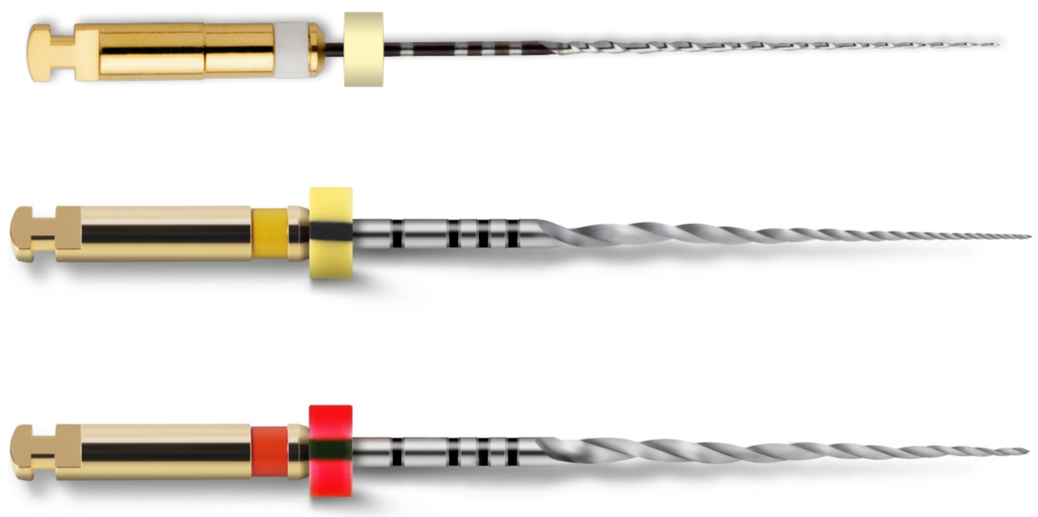

Figure 3.13: One G (Micro-Mega) and ProTaper NEXT X1 and X2 (Dentsply Sirona)

3.6.6 Group 6: Glide Path Enlargement with One G and Shaping with WaveOne Gold (OG/WOG)

The canals in the WaveOne Gold group were prepared through the use of the Primary WaveOne Gold file in the X-Smart Plus motor after glide path enlargement with One G (n =15), according to the manufacturer's instructions (Fig. 3.14).

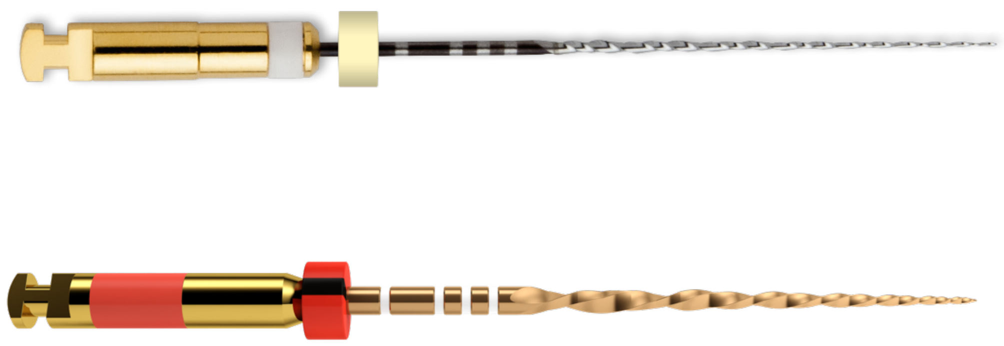

Figure 3.14: One G (Micro Mega) and Primary WaveOne Gold (Dentsply Sirona)

3.6.7 Group 7: Glide Path Enlargement with ProGlider and Shaping with OneShape (PG/OS)

The canals in the OneShape group were prepared by using the OneShape instrument in the X-Smart Plus motor after glide path enlargement with ProGlider (n =15), according to the manufacturer's instructions (Fig. 3.15).

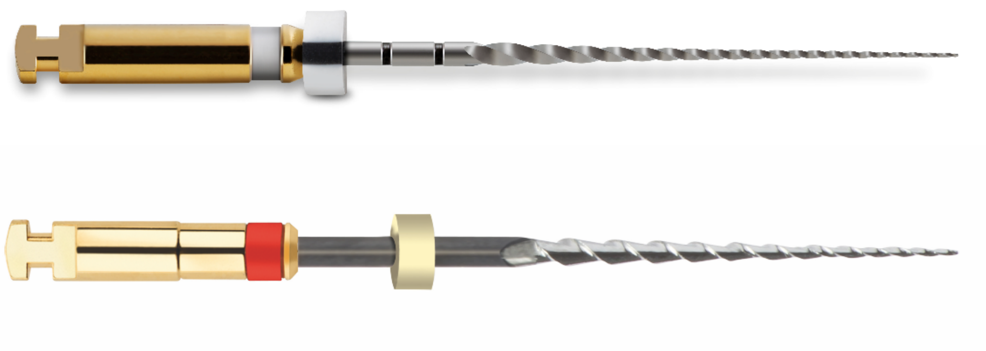

Figure 3.15: ProGlider (Dentsply Sirona) and OneShape (Micro-Mega)

3.6.8 Group 8: Glide Path Enlargement with ProGlider and Shaping with ProTaper NEXT (PG/PTN)

The canals in the ProTaper NEXT group were prepared with the use of the X1 and X2 files in the X-Smart Plus motor after glide path enlargement with ProGlider (n =15), according to the manufacturer's instructions (Fig. 3.16).

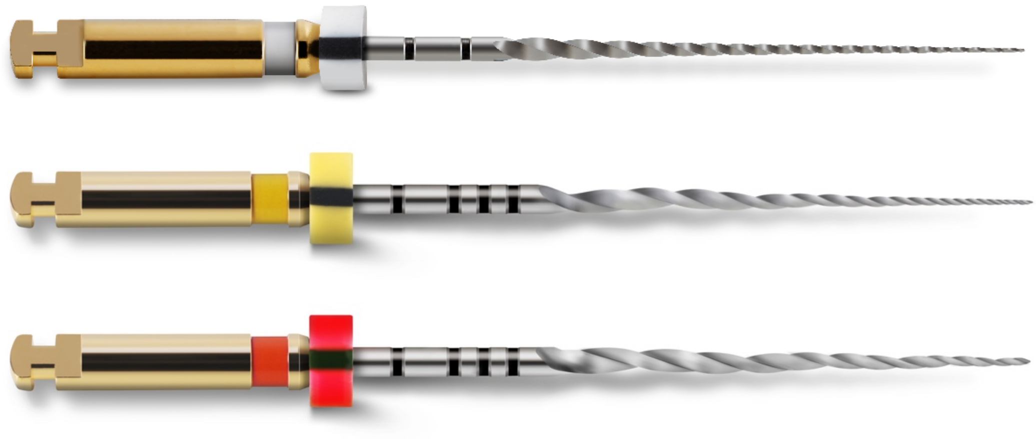

Figure 3.16: ProGlider and ProTaper NEXT X1 and X2 (Dentsply Sirona)

3.6.9 Group 9: Glide Path Enlargement with ProGlider and Shaping with WaveOne Gold (PG/WOG)

The canals in the WaveOne Gold group were prepared with the use of the Primary WaveOne Gold file in the X-Smart Plus motor after glide path enlargement with ProGlider (n =15), according to the manufacturer's instructions (Fig. 3.17).

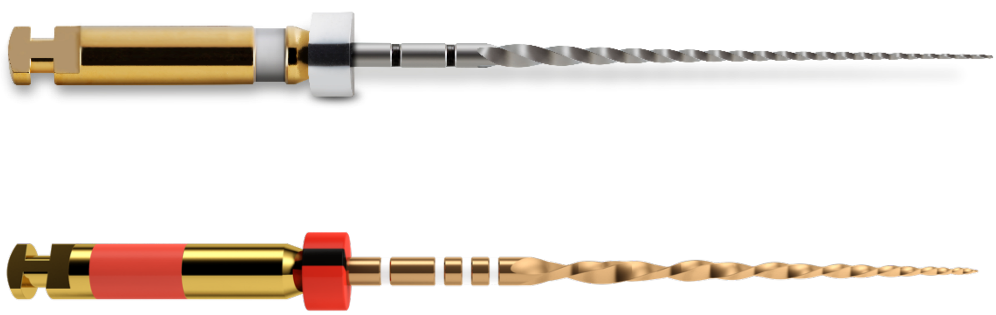

Figure 3.17: ProGlider and Primary WaveOne Gold (Dentsply Sirona)

All canals were shaped with the preparation instruments by the same operator. Throughout, the instrumentation process 5 ml of 3.5% NaOCl was used as an irrigation solution. Each file from the different systems was used to prepare only one canal before it was discarded. Patency was maintained with an ISO size 08 K-Flex file during the preparation procedures.

After shaping, teeth were finalised into nine groups of fifteen canals each, according to the mechanical glide path and shaping systems used during canal preparation: Group K/OS (K-FlexoFile + OneShape); Group K/PTN (K-FlexoFile + ProTaper NEXT); Group K/WOG (K-FlexoFile + Primary WaveOne Gold); Group OG/OS (One G + OneShape); Group OG/PTN (One G + ProTaper NEXT); Group OG/WOG (One G + Primary WaveOne Gold); Group PG/OS (ProGlider + OneShape); Group PG/PTN (ProGlider + ProTaper NEXT); and Group PG/WOG (ProGlider + Primary WaveOne Gold).

After canal preparation with the different shaping instruments all the canals were dried with paper points (ISO size 25) (Dentsply Sirona). The teeth were placed in the same custom moulds as for the pre-instrumentation scan (Scan 1) and glide path scan (Scan 2) and again scanned by the XTH 225 ST micro-focus X-ray computed tomography system to generate the final canal-shaping scan (Scan 3) for each tooth.

VGStudioMax software again enabled merging the 3D images of the shaped canals on the images from the first two scans (pre-instrumentation and glide path scans)(Fig. 3.18). Canals from Scan 3 were superimposed on corresponding canals from Scan 1 to measure the changes following canal preparation with the shaping instruments.

Figure 3.18: Canal-shaping path scan (Scan 3) superimposed on pre-instrumentation scan (Scan 1) and glide path (Scan 2) scan

3.7 Image Analysis

The method described by Gambill, Alder and Del Rio (1996) was used to measure canal transportation and centering Canal transportation and centering ratios were evaluated after glide path preparation (Fig. 3.19) and after shaping of the root canals with the preparation instruments (Fig. 3.20).

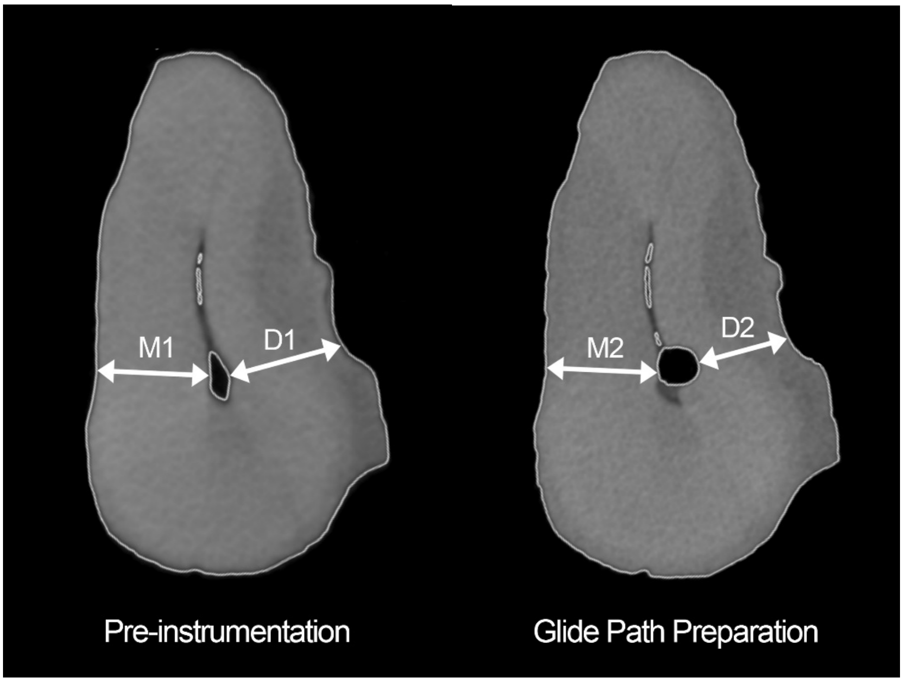

Figure 3.19: Pre-instrumentation- and post-glide-path-preparation CBCT images showing the effect of glide path preparation and points of measurements used for determination of canal transportation and centering ratio

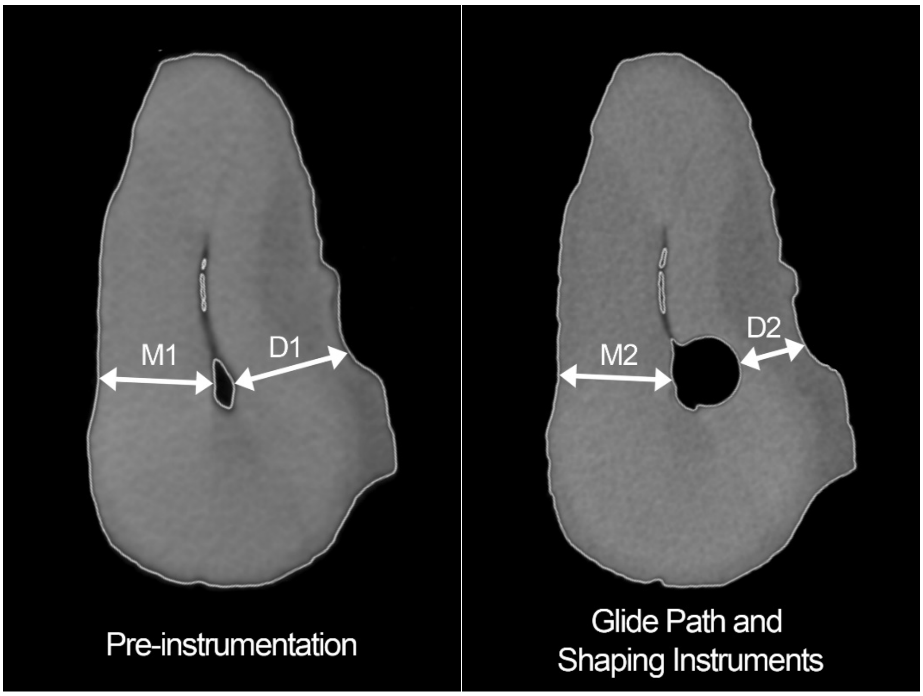

Figure 3.20: Pre-instrumentation- and post-canal-shaping CBCT images showing the effect of glide path preparation and points of measurements used for determination of canal preparation and points of measurements used for determination of canal transportation and centering ratio

The shortest distance from the prepared canal to the mesial or distal wall of the tooth at three different levels from the root apex was measured. Centering ratio and canal transportation were measured at three different lengths from the anatomical apex of the mesio-buccal root canals. A cross section at levels 2 mm (apical), 5 mm (midroot) and 9 mm (coronal) was evaluated according to the equations set out immediately below.

Canal centering ratio = (M1-M2)/(D1-D2) where (D1-D2 > M1-M2) or (D1-D2)/(M1-M2) where (M1-M1) > (D1-D2). A value/ratio closest to 1 indicates perfect centering ability.

Canal transportation = (M1-M2) – (D1-D2). A value closest to 0 indicates no transportation. The higher the value the greater the transportation.

Where:

M1: Shortest distance from the mesial margin of tooth measured to the mesial margin of uninstrumented canal.

M2: Shortest distance from mesial margin of tooth measured to the mesial margin of the instrumented canal.

D1: Shortest distance from the distal margin of tooth measured to the distal margin of the uninstrumented canal.

D2: Shortest distance from the distal margin of tooth measured to the distal margin of the instrumented canal.

Canal transportation and centering ratios were evaluated after glide path preparation and after final preparation with the shaping instruments. All micro-CT measurements were calculated by a skilled third-party operator to avoid bias but were validated by an experienced clinician. Data was recorded on a Microsoft Excel (Microsoft Corp., Redmond, Washington) spread sheet and verified.

Before glide path preparation, after glide path preparation and after canal instrumentation with the shaping instruments the mesio-buccal canals of each specimen were traced and the total volume was measured. The removed dentine volumes were determined in mm^3 for each root canal by, first, subtracting the pre-instrumentation canal volume from the glide path volume and, second, the pre-instrumentation canal volume from the canal instrumentation volume (Figure 3.21)(Hashem et al. 2012).

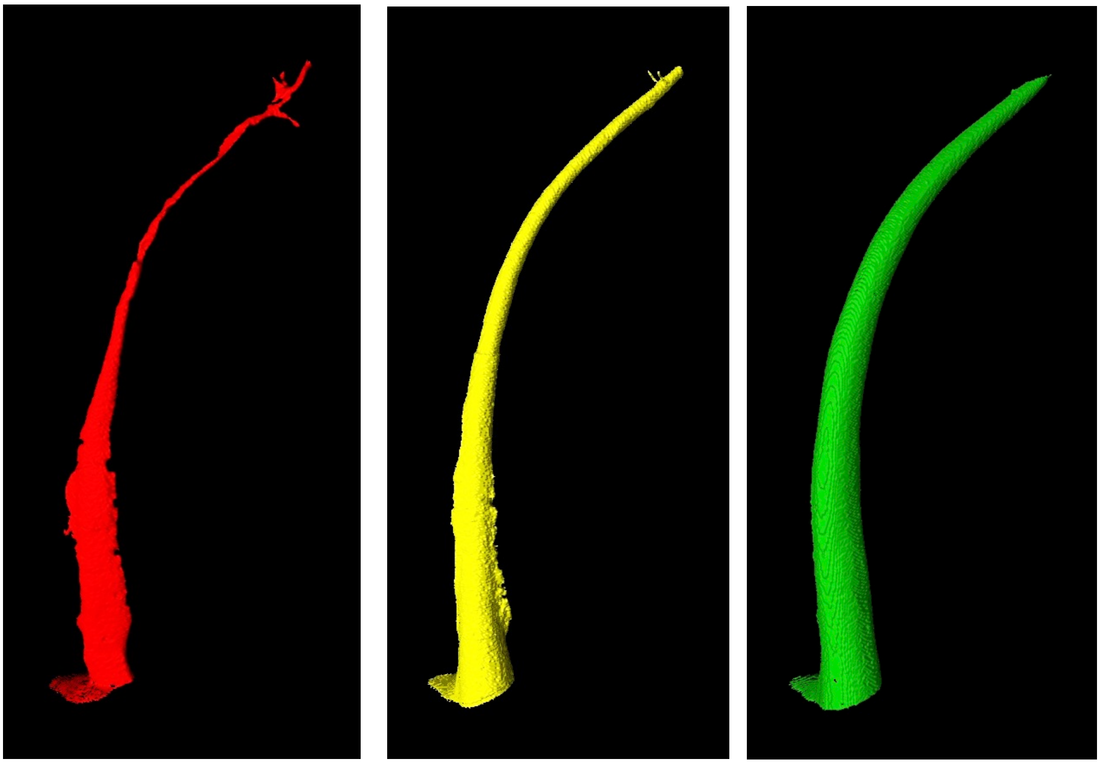

Figure 3.21: Three-dimensional reconstructions of a mesio-buccal root canal system of a maxillary molar. Bucco-lingual views of root canal volume after pre-instrumentation (*red)*, after glide path preparation (*yellow*) and after canal preparation with the shaping instruments (*green*)

3.8. Statistical Analysis

Data analysis was done in conjunction with a biostatistician. Canal transportation, centering ratio values, and volume of removed dentine values were compared between the experimental groups by using either one-way

ANOVA (parametric distributions) or the Kruskal-Wallis H test (non-parametric distributions). Statistical significance was set at $p < 0.05$.

All statistical procedures were performed on SAS (SA Institute Inc, Carey, NC, USA) release 9.4 running under Microsoft Windows (Microsoft Corp.).

Chapter 4: Results

4.1. Centering Ability of Glide Path Instruments

The mean canal centering ability values of the glide path instruments were compared at levels 2 mm (apical), 5 mm (midroot), and 9 mm (coronal) from the anatomical apex of the root. Centering ability was measured for each of the three glide path preparation groups. A value/ratio closest to 1 indicated a perfect centering ability. Centering ability was measured for each of the three glide path preparation groups. The data collected for the centering ratio values showed a parametric distribution; thus, one-way ANOVA was used to compare among groups.

4.1.1. Centering Ratio Values of Glide Path Instruments in the Apical Third

The mean centering ratio values of the glide path instruments in the apical third of the roots is presented in Figure 4.1. The means, standard deviations, minimum, and maximum values and significant differences are summarised in Table 4.1.

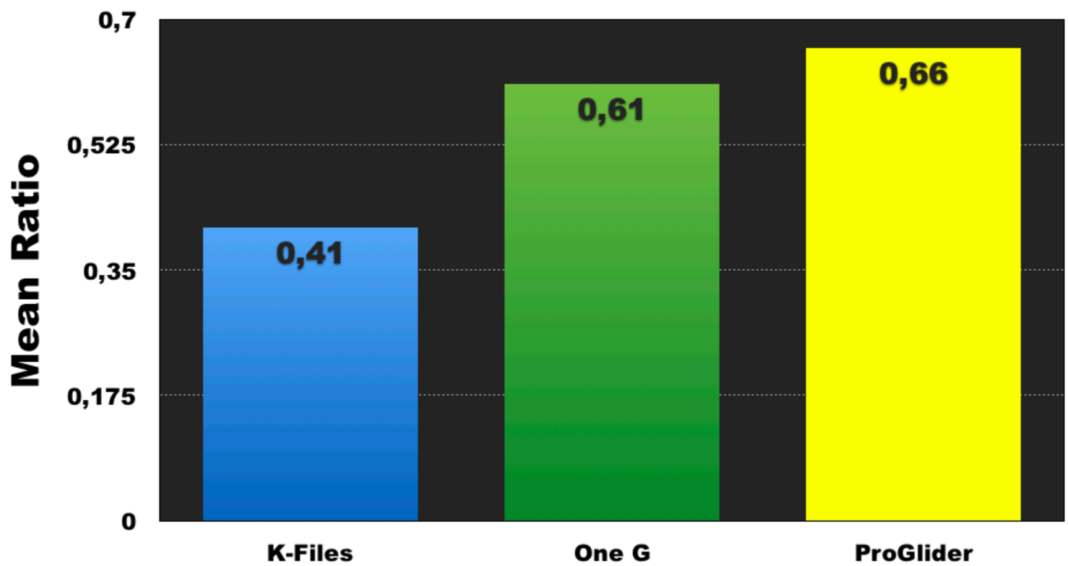

Figure 4.1: Mean centering ratio values of glide path instruments in the apical third

The best mean centering ratio value was observed with ProGlider (0.66 ± 0.17) followed by One G (0.61 ± 0.13) and then K-Files (0.41 ± 0.17). There was a statistically significant difference between the mean centering ratio values of K-Files compared to One G ($p<0.05$) and to ProGlider ($p<0.05$). There was no statistically significant difference between the centering ratio values of One G and ProGlider ($p=0.1006$).

Figure 4.2 is a representative sample from the K-File group showing a poor centering ratio in the apical third of the root canal and Figure 4.3 is a representative sample from the ProGlider group showing a good centering ratio at the apical third of the root canal.

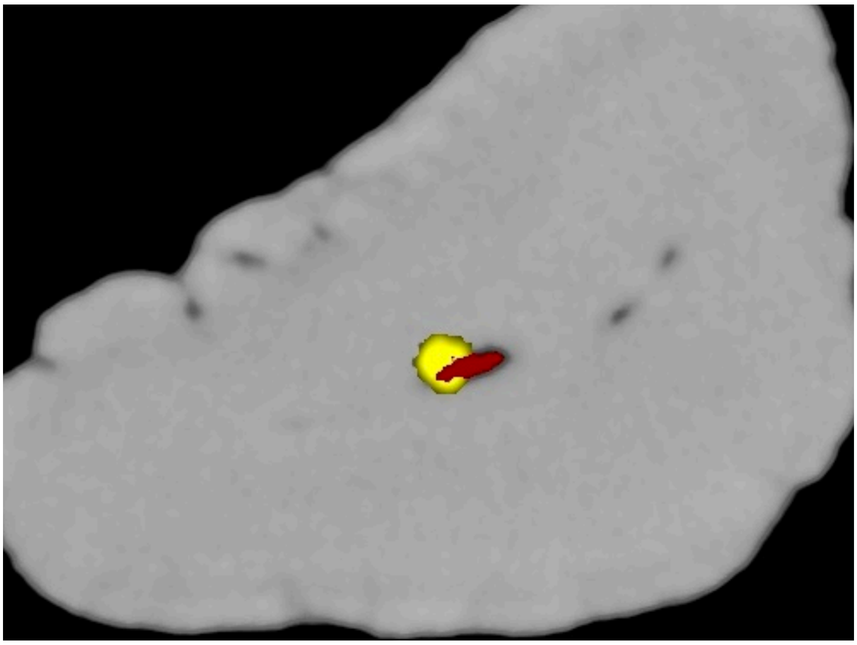

Figure 4.2: A representative sample from the K-File group showing a poor centering ratio at the apical third of the root canal (*red* – pre-instrumentation area; *yellow* – effect of glide path preparation)

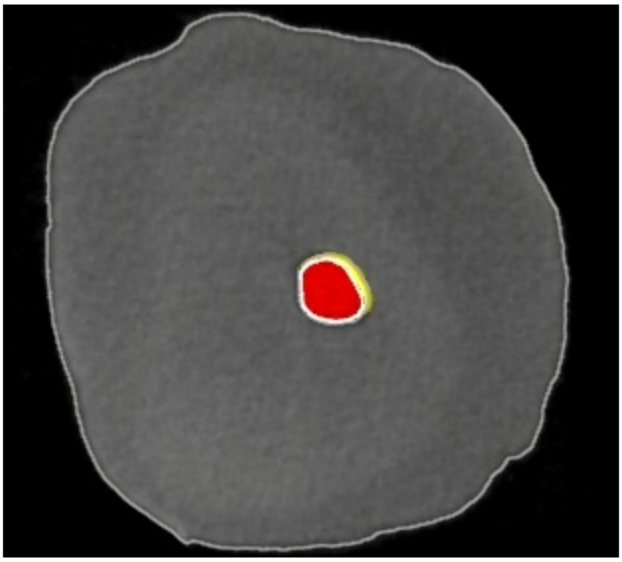

Figure 4.3: A representative sample from the ProGlider group showing a good centering ratio at the apical third of the root canal (*red* – pre-instrumentation area; *yellow* – effect of glide path preparation)

4.1.2. Centering Ratio Values of Glide Path Instruments in the Middle Third

Figure 4.4 depicts the mean centering ratio values of the glide path instruments in the middle third of the roots. The descriptive statistics are summarised in Table 4.2.

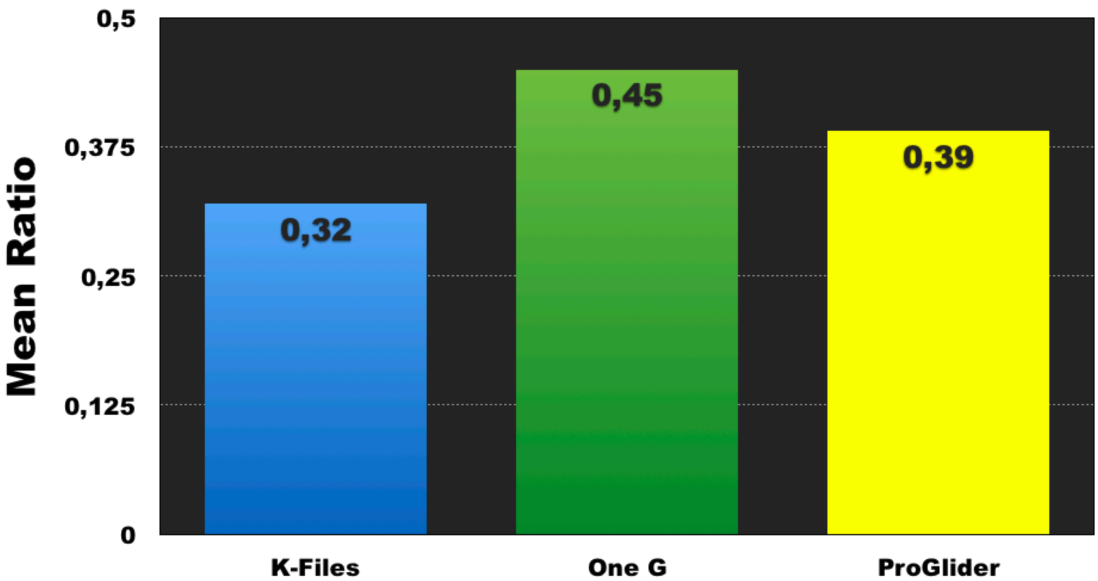

Figure 4.4: Mean centering ratio values of glide path preparation instruments in the middle third

The best mean centering ratio value in the middle third was observed with One G (0.45 ± 0.18) followed by ProGlider (0.39 ± 0.15) and then K-Files (0.32 ± 0.16). There was a statistically significant difference between the mean centering ratio values of K-Files compared to One G (p=0.0005) and to ProGlider (p=0.0476). No statistically significant difference was found between the mean centering ratio values of One G and ProGlider (p=0.01227). Figure 4.5 shows a representative sample from the One G group, which shows a good centering ratio at the middle third of the root canal.

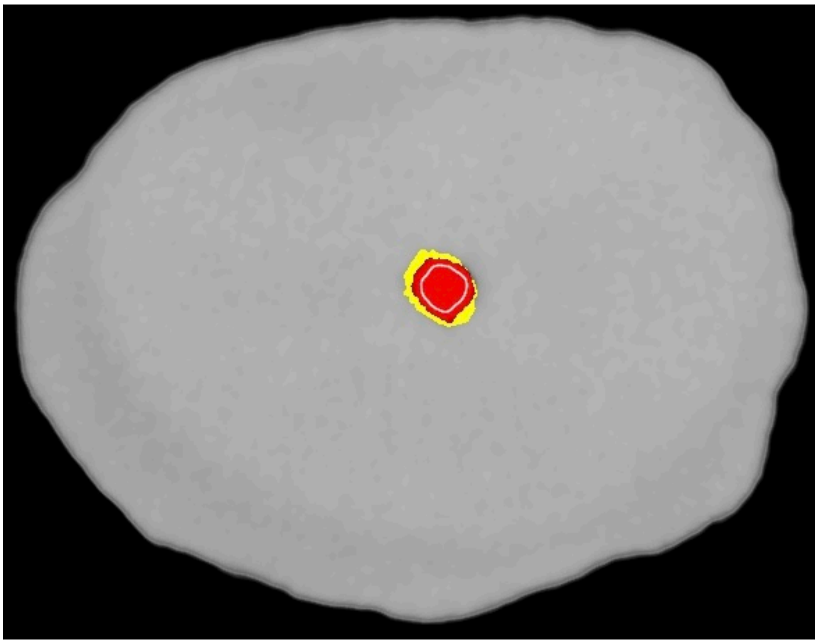

Figure 4.5: A representative sample from the One G group showing a good centering ratio at the middle third of the root canal (*red* – pre-instrumentation area; *yellow* – effect of glide path preparation)

4.1.3. Centering Ratio Values of Glide Path Instruments in the Coronal Third

The mean centering ratio values of the glide path instruments in the coronal third of the roots are presented in Figure 4.6. The descriptive statistics are summarised in Table 4.3.

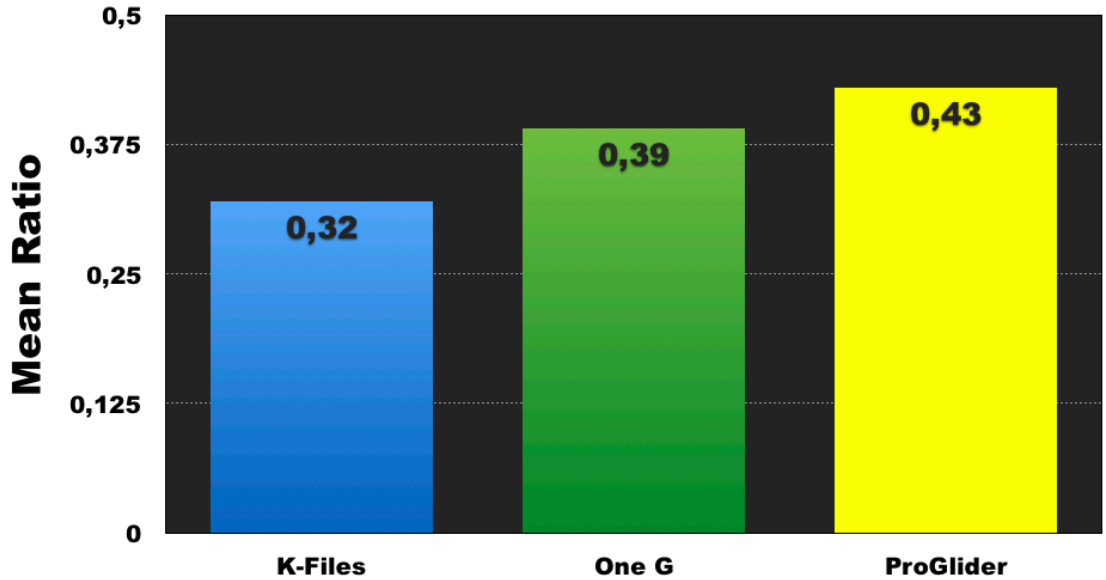

Figure 4.6: Mean centering ratio values of glide path preparation instruments in the coronal third

In the coronal third of the root, the best mean centering ratio value was observed with ProGlider (0.43 ± 0.15) followed by One G (0.39 ± 0.20) and then K-Files (0.32 ± 0.14). No statistically significant difference was found between the mean centering ratio values of K-Files compared to ProGlider (p=0.0036) and to One G (p=0.05). Neither was there a statistically significant difference between the mean centering ratio values of One G and ProGlider (p=0.321).

Figure 4.7 depicts a representative sample from the ProGlider group showing a good centering ratio at the coronal third of the root canal.

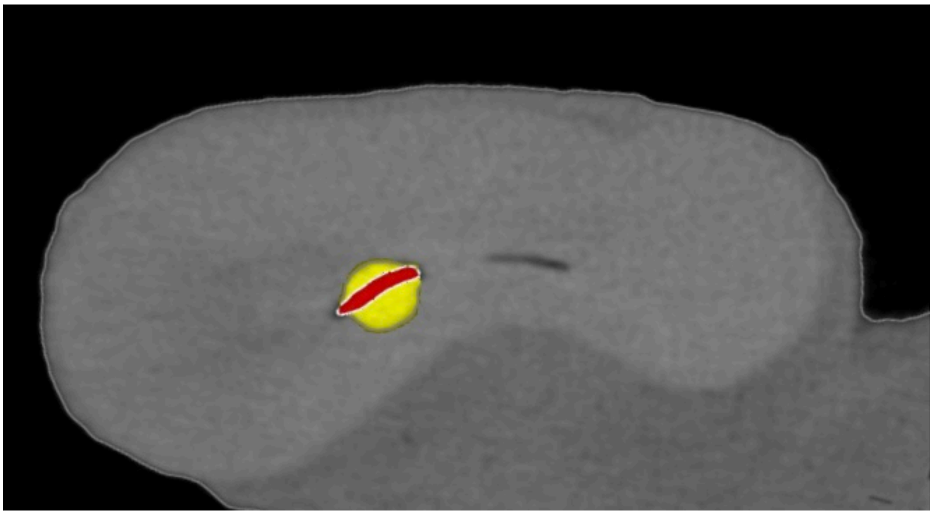

Figure 4.7: A representative sample from the ProGlider group showing a good centering ratio at the coronal third of the root canal (*red* – pre-instrumentation area; *yellow* – effect of glide path preparation)

4.1.4. Combined Centering Ratio Values of Glide Path Instruments

The combined results of the apical, middle, and coronal thirds for the mean centering ratio values for each group after glide path enlargement are illustrated in Figure 4.8. The descriptive statistics are summarised in Table 4.4.

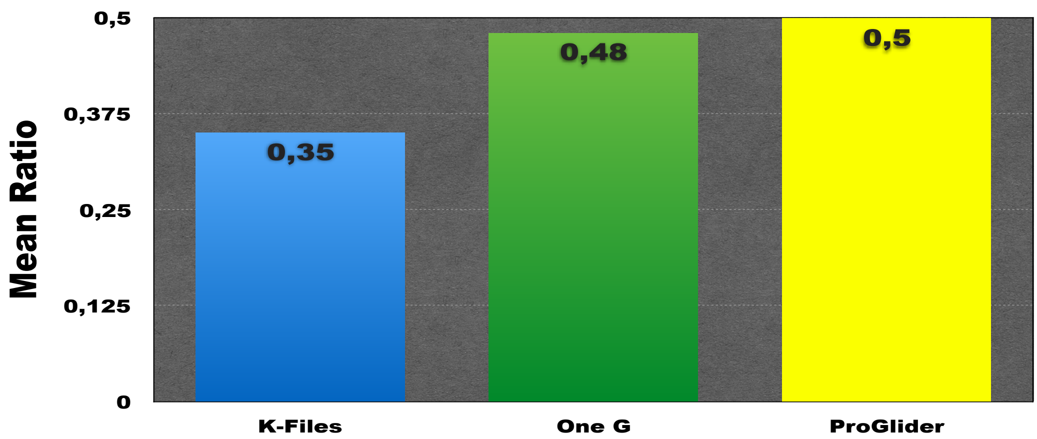

Figure 4.8: Combined mean centering ratio values of glide path preparation instruments

The best mean centering ratio value was observed with ProGlider (0.50 ± 0.20 mm) followed by One G (0.48 ± 0.20) and then K-Files (0.35 ± 0.16). There was a statistically significant difference between the mean centering ratio values of K-Files compared to One G and to ProGlider ($p<0.005$). No statistically significant difference was found between the mean centering ratio values of One G and ProGlider ($p=5890$).

4.2. Canal Transportation of Glide Path Preparation Instruments

The mean canal transportation values of the glide path instruments were compared at levels 2 mm (apical), 5 mm (midroot), and 9 mm (coronal) from the anatomical apex of the tooth. A transportation value closest to 0 indicated that no transportation occurred. The data collected for transportation values showed a non-parametric distribution; thus, the Kruskal-Wallis H test was used to compare the groups.

4.2.1. Canal Transportation Values of Glide Path Instruments in the Apical Third

Figure 4.9 depicts the median (Interquartile Range (IQR)) transportation values of the glide path instruments at the apical third of the roots. The descriptive statistics are summarised in Table 4.5.

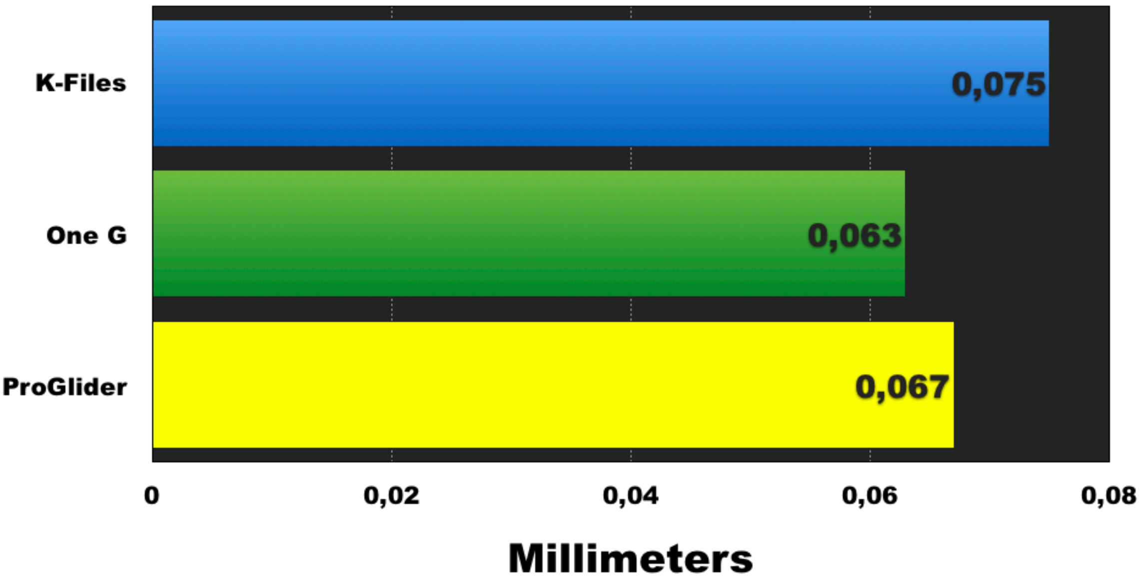

Figure 4.9: Median canal transportation values of glide path instruments in the apical third

In the apical third of the root, the highest median transportation value was observed with K-Files (0.075 ± 0.03 mm) followed by ProGlider (0.067 ± 0.01 mm) and then One G (0.063 ± 0.02 mm). There was a statistically significant difference between the median transportation values of K-Files compared to One G (p=0.0008) and to ProGlider (p=0.0376), but no statistically significant difference was found between the median transportation values of ProGlider and One G (p=0.2102). Figure 4.10 presents a representative sample from the K-File group that shows transportation at the apical third of the root canal.

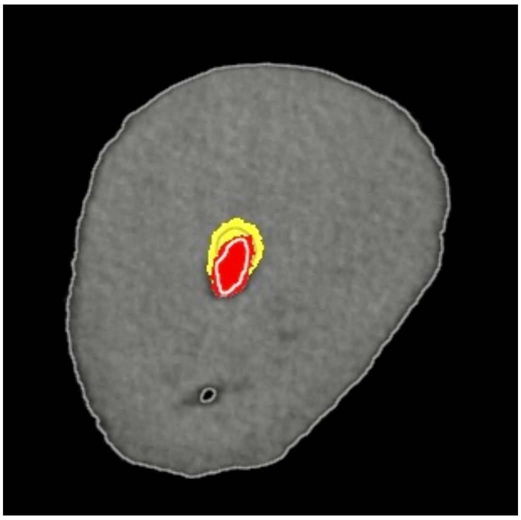

Figure 4.10: A representative sample from the K-File group showing transportation at the apical third of the root canal (*red* – pre-instrumentation area; *yellow* – effect of glide path preparation)

4.2.2. Canal Transportation Values of Glide Path Instruments in the Middle Third

The median (IQR) transportation values of the glide path instruments at the middle third of the roots are presented in Figure 4.11. The descriptive statistics are summarised in Table 4.6.

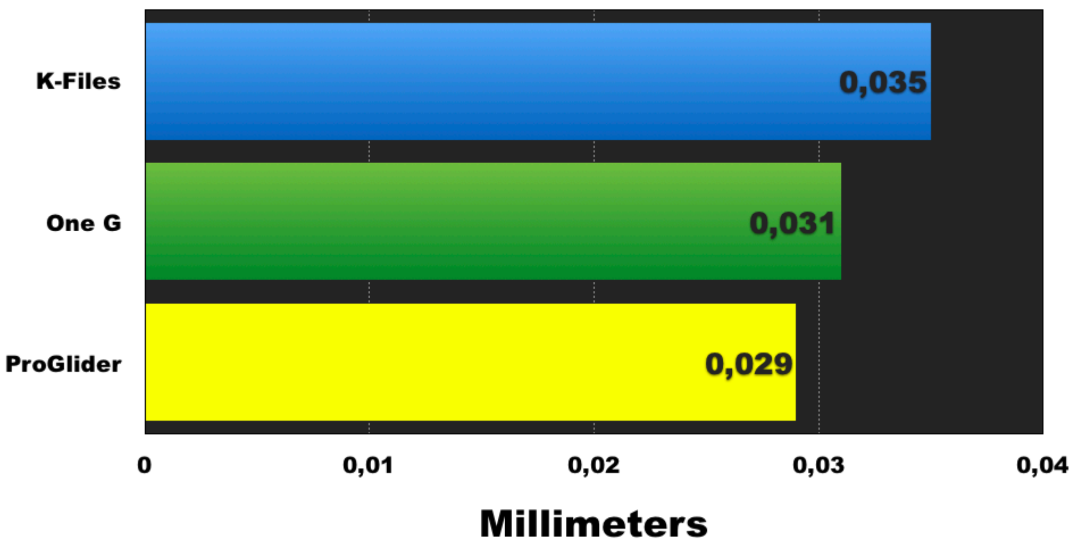

Figure 4.11: Median canal transportation values of glide path instruments in the middle thirds

The highest median transportation value in the middle third was observed with K-Files (0.35 ± 0.20 mm) followed by One G (0.031 ± 0.01 mm) and then ProGlider (0.029 ± 0.02 mm). There were no statistically significant differences between the median transportation values of the various rotary file groups (p=0.1386). Figure 4.12 presents a representative sample from the One G group and shows a minimal amount of transportation at the middle third of the root canal.

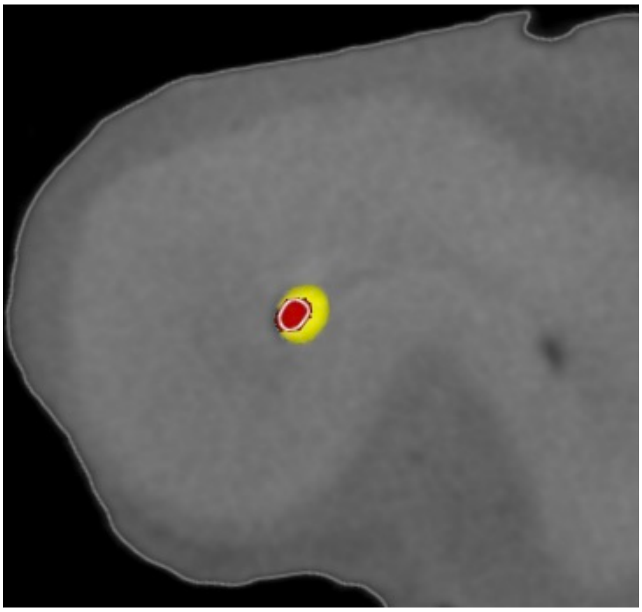

Figure 4.12: A representative sample from the One G group showing a minimal amount of transportation at the middle third of the root canal (*red* – pre-operative area; *yellow* – effect of glide path preparation)

4.2.3. Canal Transportation Values of Glide Path Instruments in the Coronal Third

Figure 4.13 depicts the median (IQR) transportation values of the glide path instruments at the apical third of the roots. The descriptive statistics are summarised in Table 4.7.

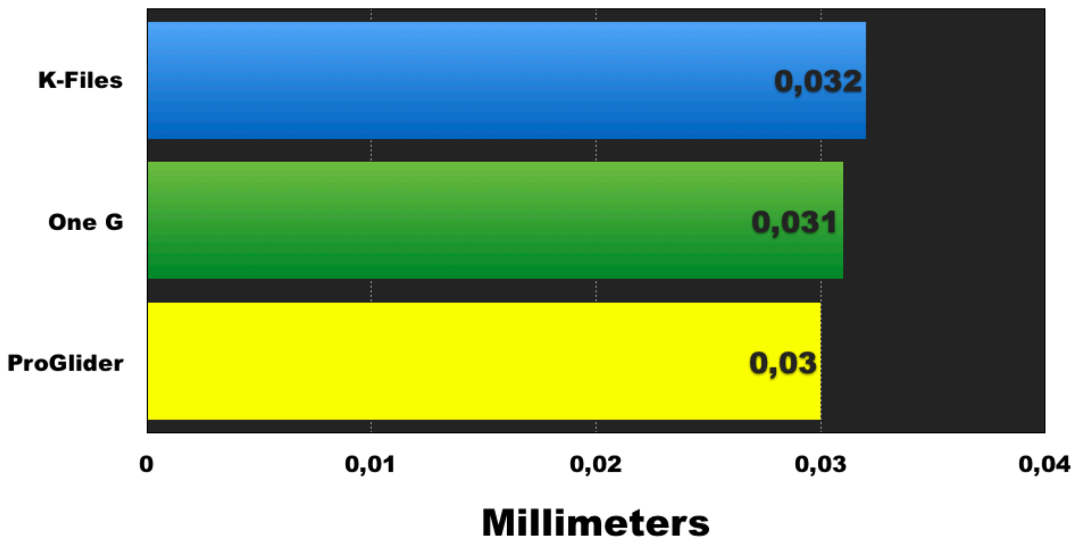

Figure 4.13: Median canal transportation values of glide path instruments in the coronal third

In the coronal third of the root, the highest median transportation value was observed with K-Files (0.32 ± 0.02 mm) followed by One G (0.31 ± 0.01 mm) and then ProGlider (0.30 ± 0.02 mm). No statistically significant differences were found between the median transportation values of the different groups (p=0.495). Figure 4.14 depicts a representative sample from the ProGlider group, showing a good centering ratio in the coronal third of the root canal.

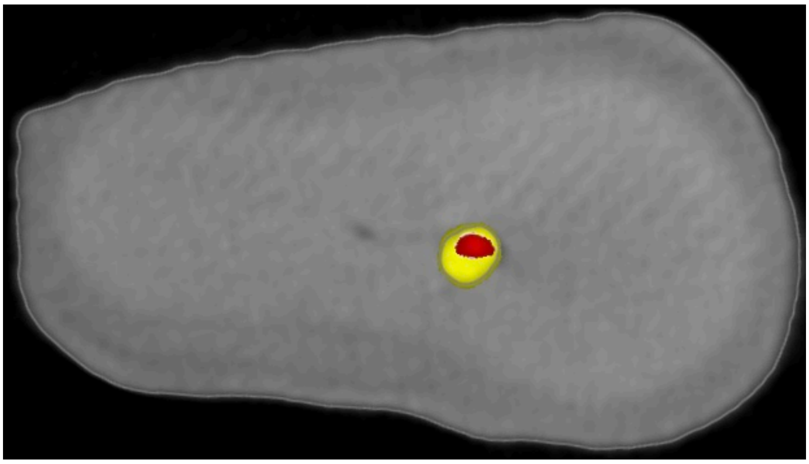

Figure 4.14: A representative sample from the ProGlider group showing a good centering ratio at the coronal third of the root canal (*red* – pre-operative area; *yellow* – effect of glide path preparation)

4.2.4. Combined Canal Transportation Values of Glide Path Instruments

The combined results of the apical, middle, and coronal thirds for the median (IQR) transportation values for each group after glide path enlargement are illustrated in Figure 4.15. The descriptive statistics are summarised in Table 4.8.

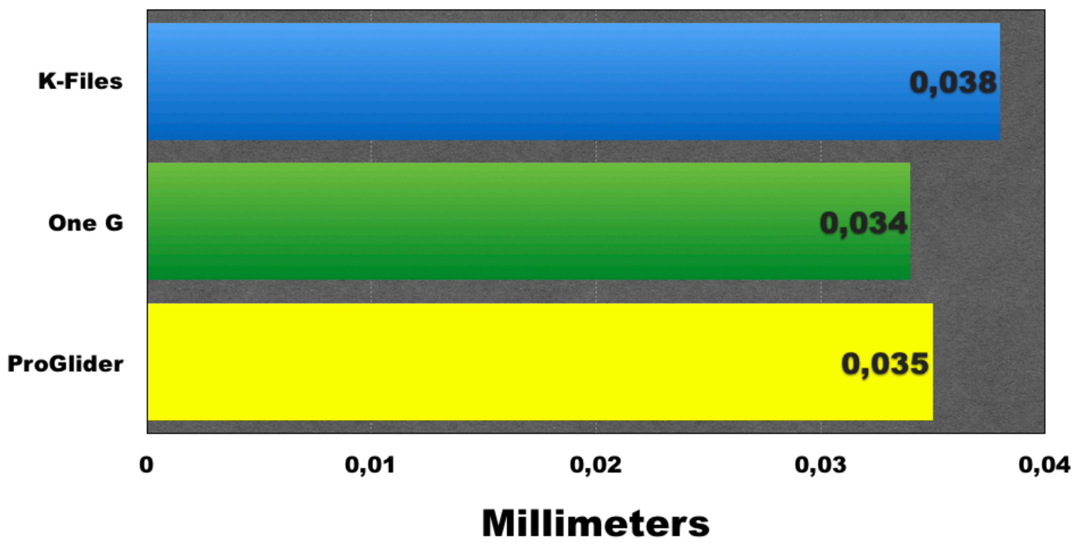

Figure 4.15: Combined median canal transportation of glide path preparation instruments

The highest median transportation value was obtained with K-Files (0.038 ± 0.03 mm), followed by ProGlider (0.035 ± 0.02 mm), and then One G (0.034 ± 0.02 mm). There were no statistically significant differences between the median transportation values of the various groups (p=1336).

4.3. Volume of Dentine Removed with Glide Path Instruments

The data collected for the volume of dentine removed from the glide path instruments showed a non-parametric distribution. For this reason, the Kruskal-Wallis H test was used to compare the groups. Figure 4.16 and Table 4.9 show the results and descriptive statistics of the volumes of dentine removed for each group, respectively.

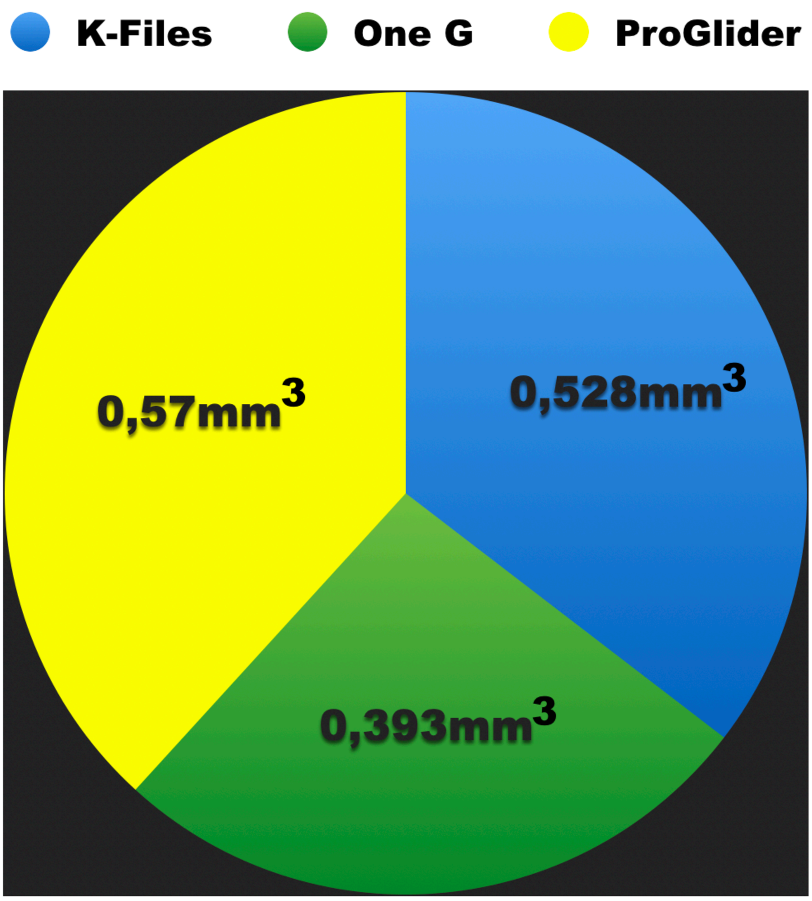

Figure 4.16: Median volume amount of dentine removed with glide path instruments

The ProGlider group recorded the highest volume of removed dentine (0.57 $mm^3 \pm 0.39$ mm^3), followed by the K-File group (0.53 $mm^3 \pm 0.34$ mm^3) and then the One G group (0.39 $mm^3 \pm 0.28$ mm^3). There were no statistically significant differences between the tested groups regarding the volume of dentine removed (p=0.1688). Figure 4.17 depicts representative 3D reconstructions of mesio-buccal root canal volumes before instrumentation (red) and after glide path preparation with the different glide path preparation groups.

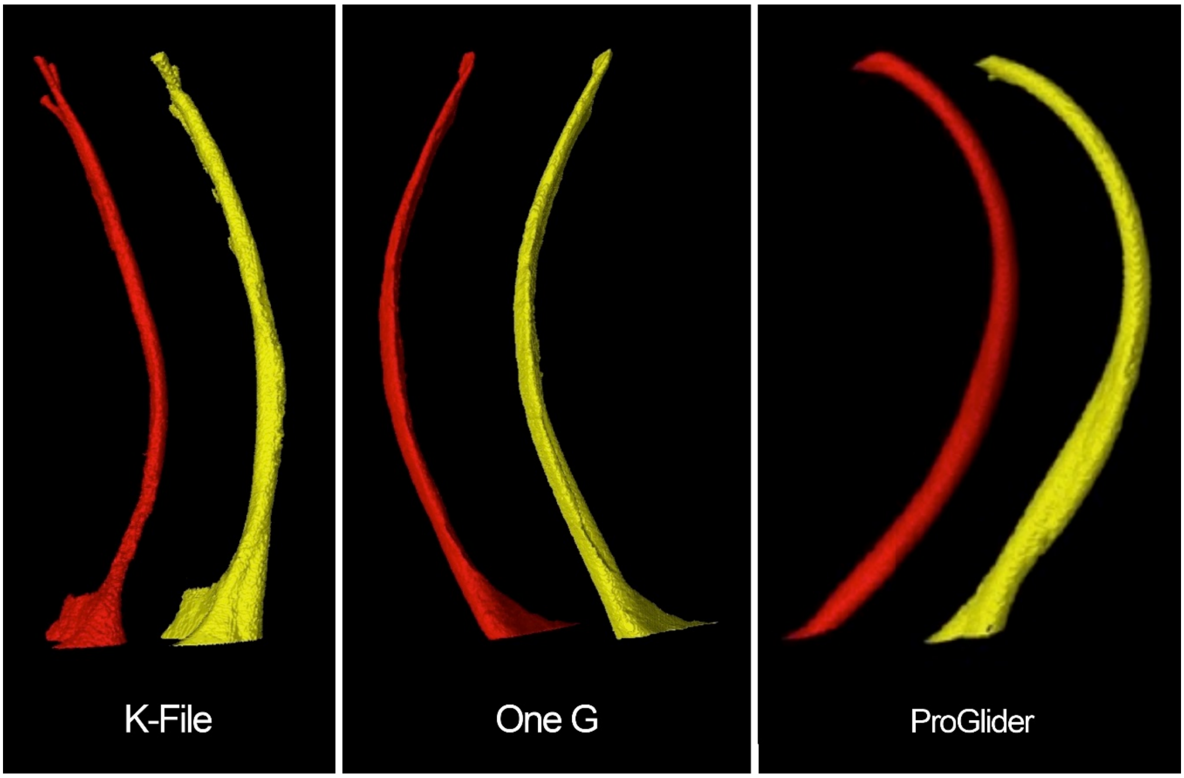

Figure 4.17: Representative 3D reconstructions of the bucco-lingual views of mesio-buccal root canal volumes, before instrumentation and after glide path preparation for the different groups (*red* – pre-instrumentation volume; *yellow* – volume after glide path preparation)

4.4. Centering Ability of Shaping Instruments

The mean canal centering ability values after shaping were compared at levels 2 mm (apical), 5 mm (midroot), and 9 mm (coronal) from the anatomical apex of the tooth. Centering ability was measured for each of the nine shaping groups. A value/ratio closest to 1 indicated a perfect centering ability. Centering ability was measured for each of the nine shaping groups.

4.4.1. Centering Ratio Values of Shaping Instruments in the Apical Third

The mean centering ratio values of the shaping instruments in the apical third of the roots is presented in Figure 4.18. The means, standard deviations, minimum, and maximum values and significant differences are summarised in Table 4.10.

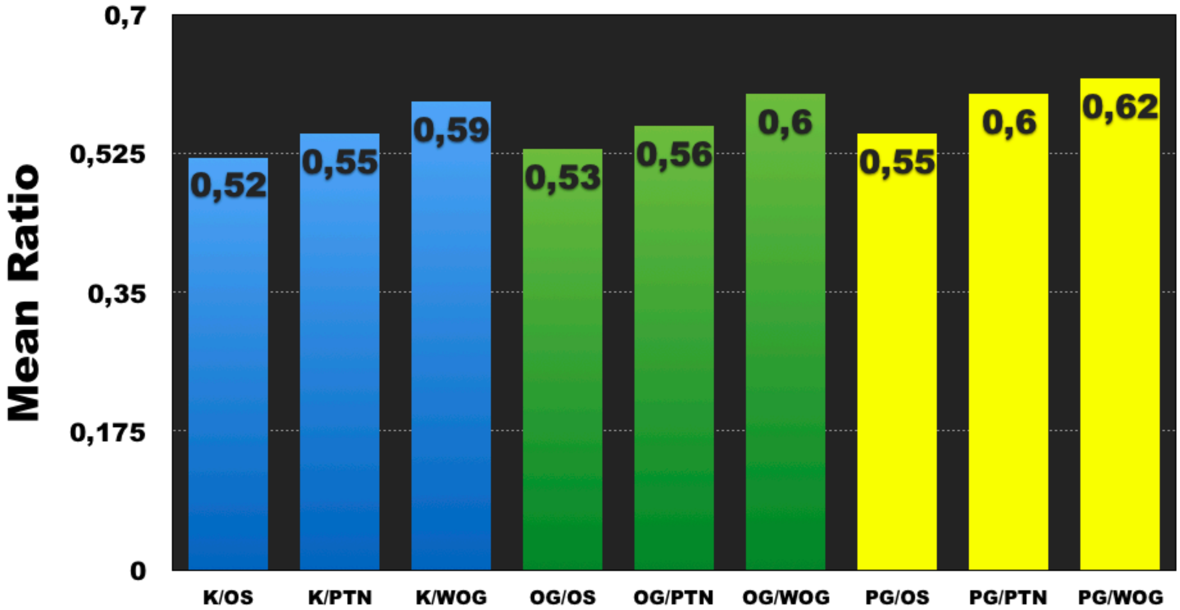

Figure 4.18: Mean centering ratio values of shaping instruments in the apical third

The data collected for the centering ratio values showed a parametric distribution, which led to the use of one-way ANOVA for comparing among groups. The best mean centering ratio value was observed in PG/WOG group (0.62 ± 0.33) and the worst mean centering ratio value was observed in K/OS group (0.52 ± 0.36). There were no statistically significant differences between the centering ratio values of the various groups (p=0.9962). Figure 4.19 portrays a representative sample from the K/OS group that shows a poor centering ratio and Figure 4.20 depicts a representative sample from the PG/WOG group that shows a good centering ratio in the apical third of the root canals.

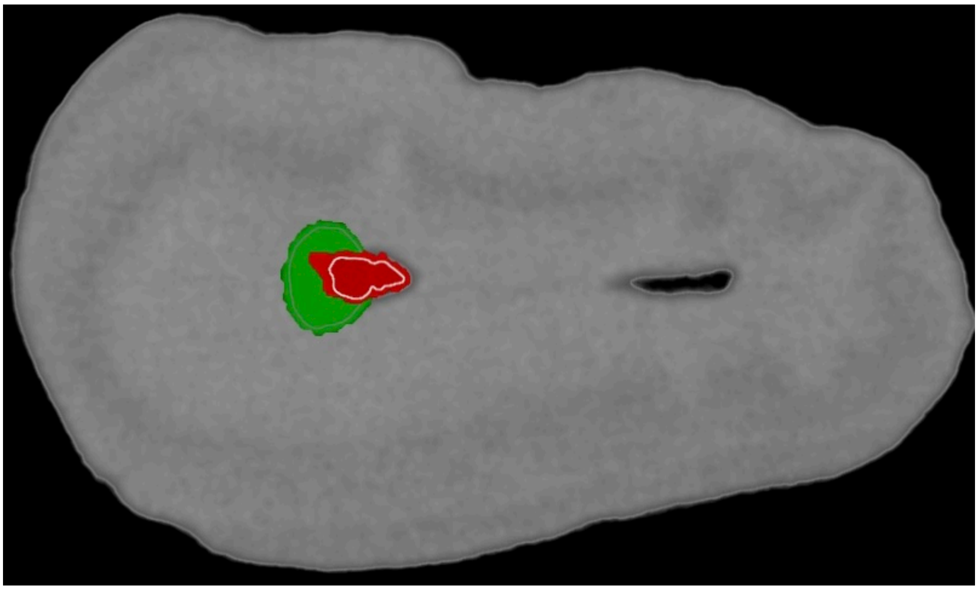

Figure 4.19: A representative sample from the K/OS group that shows a poor centering ratio at the apical third of the root canal (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument)

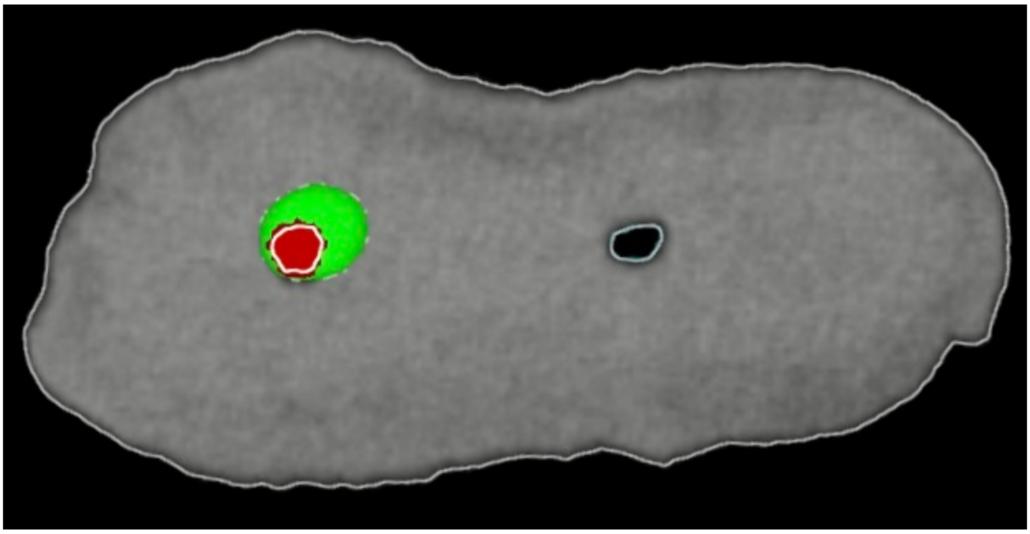

Figure 4.20: A representative sample from the PG/WOG group that shows a poor centering ratio at the apical third of the root canal (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument)

4.4.2. Centering Ratio Values of Shaping Instruments in the Middle Third

Figure 4.21 depicts the mean centering ratios values of the shaping instruments in the middle third of the roots. The descriptive statistics are summarised in Table 4.11.

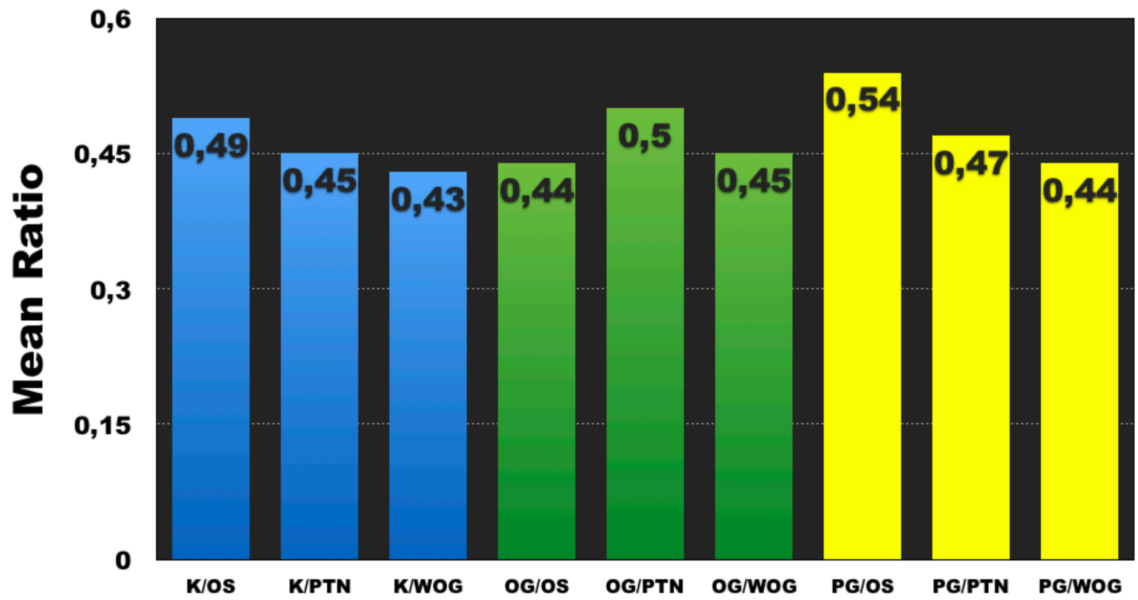

Figure 4.21: Mean centering ratio values of shaping instruments in the middle third

The data collected for the centering ratio values in the middle third showed a parametric distribution, which led to the use of one-way ANOVA for comparison among groups. The best mean centering ratio value in the middle third was observed with PG/OS group (0.54 ± 0.35) and the worst mean centering ratio value was recorded by the K/WOG group (0.43 ± 0.30). There were no statistically significant differences between the mean centering ratio values of the different groups (p=0.9888). Figure 4.22 illustrates a representative sample from the K/WOG group that shows a poor centering ratio. Figure 4.23 displays a representative sample from the PG/OS group that shows a good centering ratio in the middle third of the root canals.

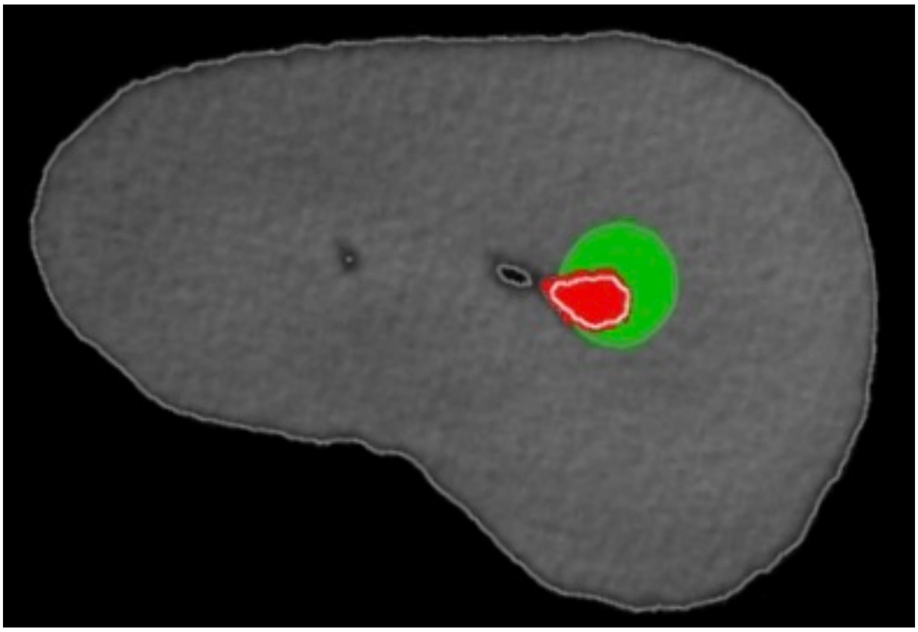

Figure 4.22: A representative sample from the K/WOG group that shows a poor centering ratio at the middle third of the root canal (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument)

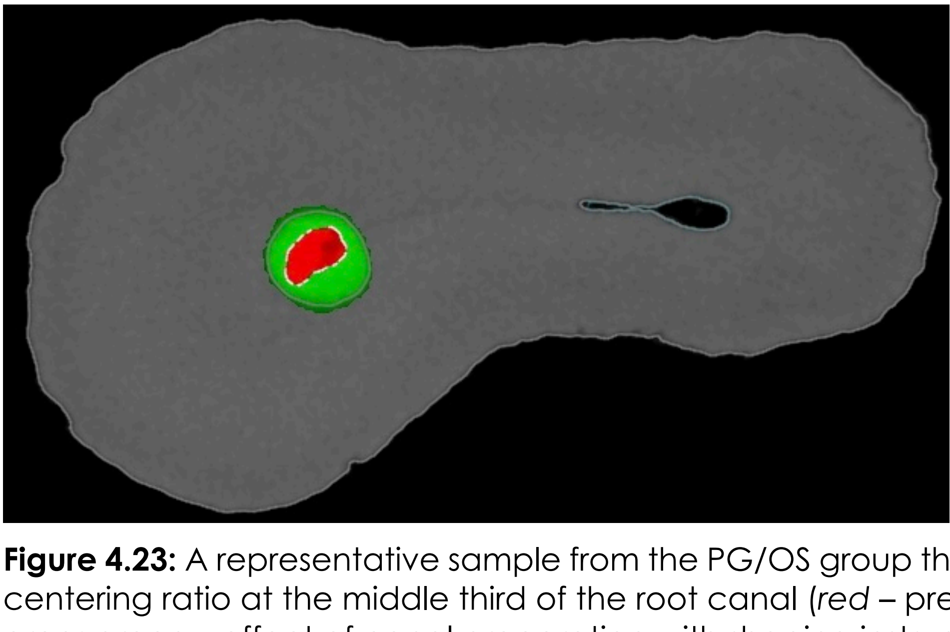

Figure 4.23: A representative sample from the PG/OS group that shows a good centering ratio at the middle third of the root canal (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument)

4.4.3. Centering Ratio Values of Shaping Instruments in the Coronal Third

The median (IQR) centering ratio values of the shaping instruments in the coronal third of the roots is presented in Figure 4.24. The descriptive statistics are summarised in Table 4.12.

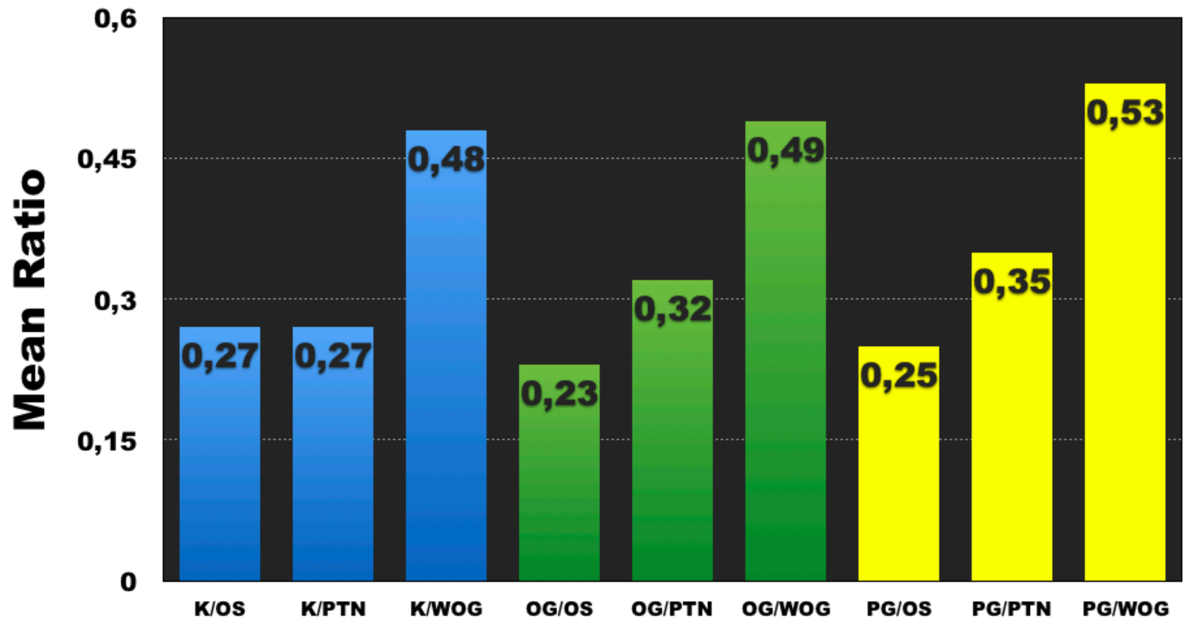

Figure 4.24: Median centering ratio values of shaping instruments in the coronal third

The data collected for the centering ratio values showed a non-parametric distribution; therefore, the Kruskal-Wallis H test was used to compare the groups. The best median centering ratio value was observed in the PG/WOG group (0.53 ± 0.89) and the worst median centering ratio value was recorded in the OG/OS group (0.23 ± 0.51). There were statistically significant differences between the median centering ratio values of the PG/WOG group and the K/OS group (p=0.0245), K/PTN group (p=0.0395), OG/OS group (p=0.0364), and PG/OS group (p=0.0274). Statistically significant differences were also found between the median centering ratio values of the OG/WOG group and the OG/OS group (p=0.0494) and between the OG/WOG group and the PG/OS group (p=0.377). Figure 4.25 is a representative sample from the OG/OS group that shows a poor centering ratio and Figure 4.26 is a representative sample from the PG/WOG group that portrays a good centering ratio in the coronal third of the root canals.

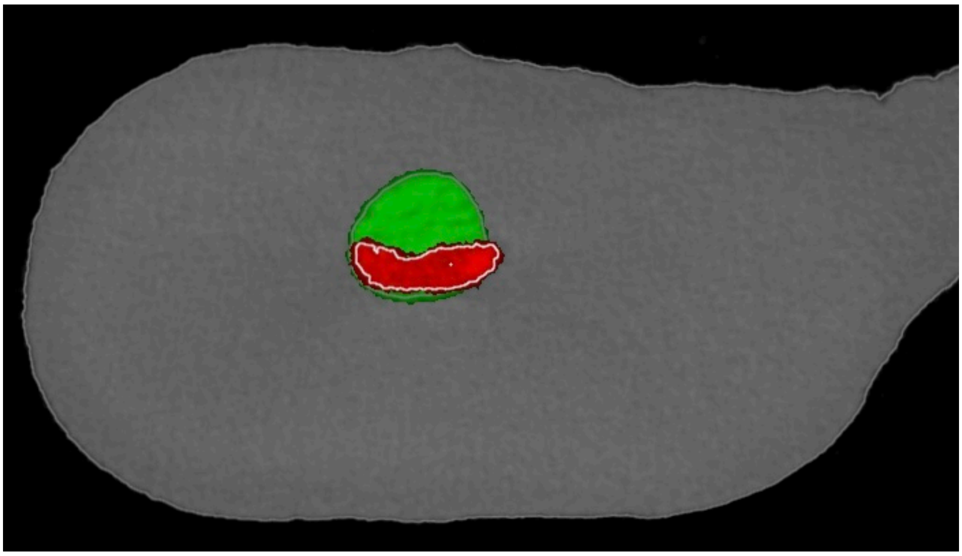

Figure 4.25: A representative sample from OG/OS group that shows a poor centering ratio at the coronal third of the root canal (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument)

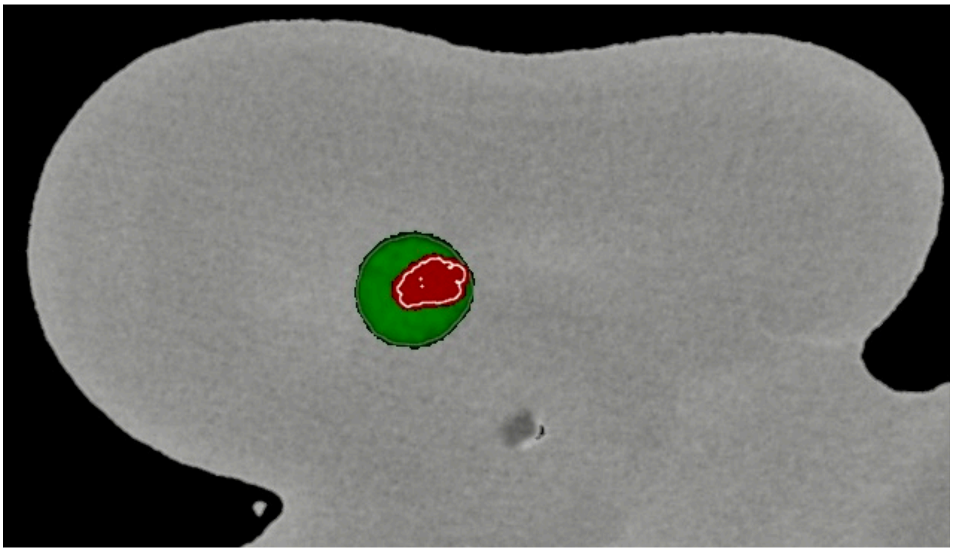

Figure 4.26: A representative sample from the PG/WOG group that shows a good centering ratio at the coronal third of the root canal (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument)

4.4.4. Combined Centering Ratio Values of Shaping Instruments

The combined results of the apical-, middle-, and coronal thirds for the mean centering ratio values for each group after canal shaping are illustrated in Figure 4.27 and Table 4.13.

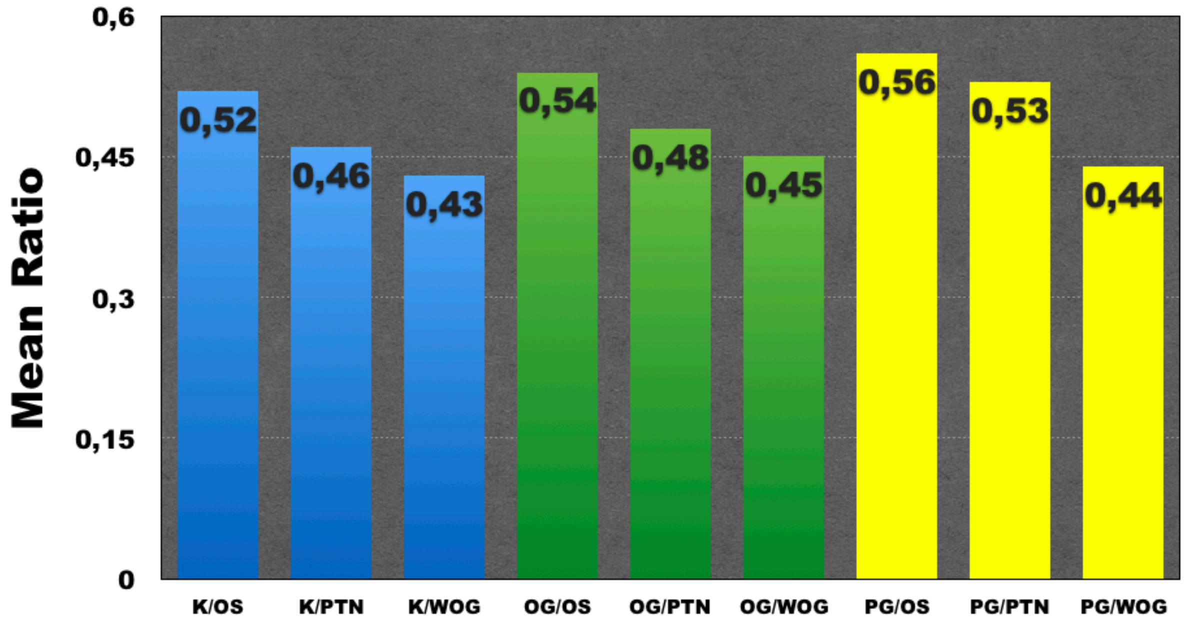

Figure 4.27: Combined mean centering ratio values of shaping instruments

The data collected showed a parametric distribution; for this reason one-way ANOVA was used for comparing among groups. The best mean centering ratio value was observed in the PG/OS group (0.56 ± 0.32) and the worst mean centering ratio value was recorded in the K/WOG group (0.43 ± 0.31). There were no statistically significant differences between the mean centering ratio values of the different groups (p=0.4494).

4.5. Canal Transportation of Shaping Instruments

The mean canal transportation values of the shaping groups were compared at levels 2 mm (apical), 5 mm (midroot), and 9 mm (coronal) from the anatomical apex of the tooth. A transportation value closest to 0 indicated that no transportation occurred. Higher values were indicative of greater transportation. The data collected for transportation values showed a parametric distribution; therefore, the one-way Anova test was used for comparing the groups.

4.5.1. Canal Transportation Values of Shaping Instruments in the Apical Third

Figure 4.28 depicts the values of the mean transportation values of the shaping instruments at the apical third of the roots. The descriptive statistics are summarised in Table 4.14.

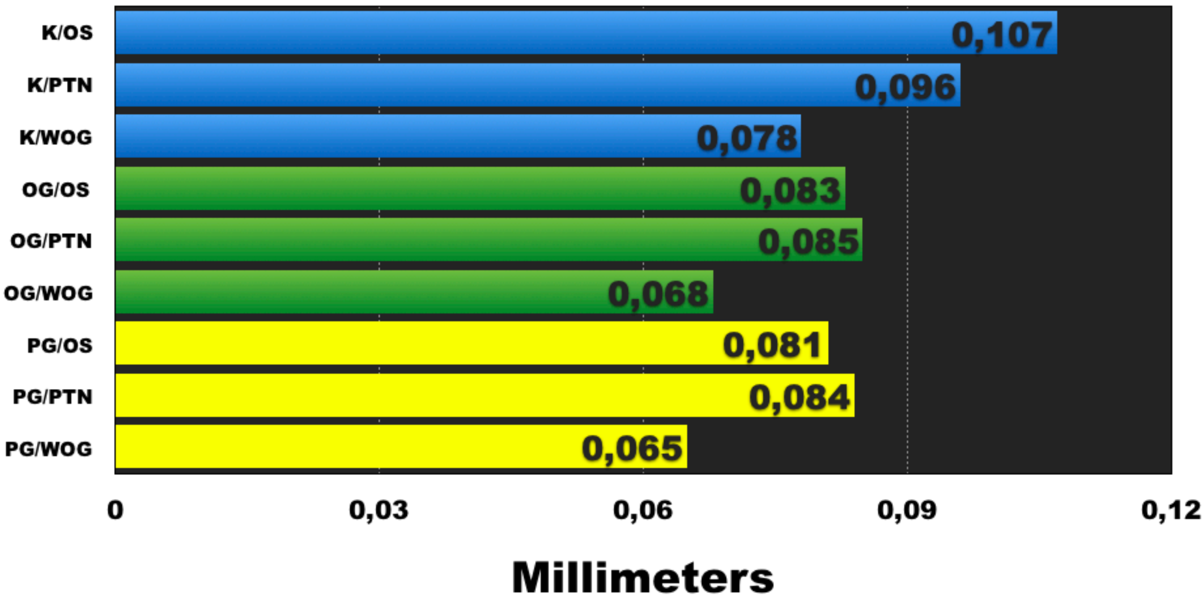

Figure 4.28: Mean canal transportation ratio values of shaping instruments in the apical third

The highest mean transportation value was observed with the K/OS group (0.107 ± 0.046 mm) and the lowest mean transportation value was recorded with the PG/WOG group (0.065 ± 0.026 mm). There were statistically significant differences between the mean transportation values of the K/OS group compared to the K/WOG group ($p=0.0069$), the OG/OS group ($p=0.0228$), the OG/PTN group ($p=0.0395$), the OG/WOG group ($p=0.0002$), the PG/OS group ($p=0.0153$), the PG/PTN group ($p=0.0326$) and the PG/WOG group ($p<0.0001$).

The test also indicated statistically significant differences between the mean transportation values of K/PTN compared to the K/WOG group (p=0.0851), the OG/WOG group (p=0.0064), and the PG/WOG group (p=0.0028), as well as between the OG/PTN group and the PG/WOG group (p=0.0496).

Figure 4.29 depicts a representative sample from the K/OS group that shows canal transportation. Figure 4.30 portrays a representative sample from the PG/WOG group that shows no canal transportation in the apical third of the root canals.

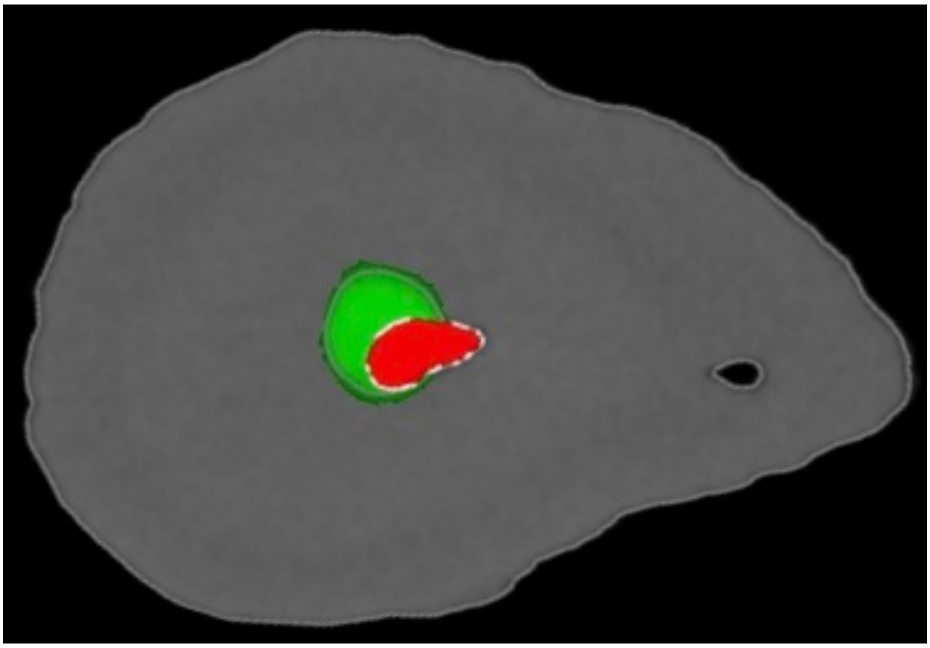

Figure 4.29: A representative sample from the K/OS group that shows canal transportation at the apical third of the root canal (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument)

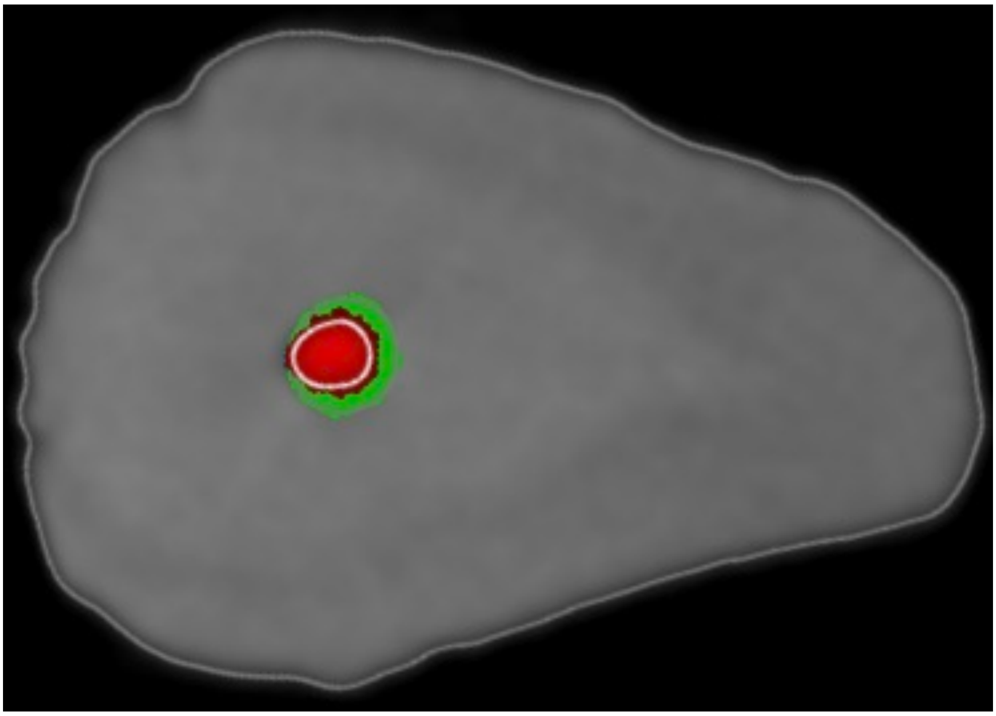

Figure 4.30: A representative sample from the PG/WOG group that shows no canal transportation at the apical third of the root canal (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument)

4.5.2. Canal Transportation Values of Shaping Instruments in the Middle Third

The mean transportation values of the shaping instruments at the middle third of the roots are presented in Figure 4.31. The descriptive statistics are summarised in Table 4.15.

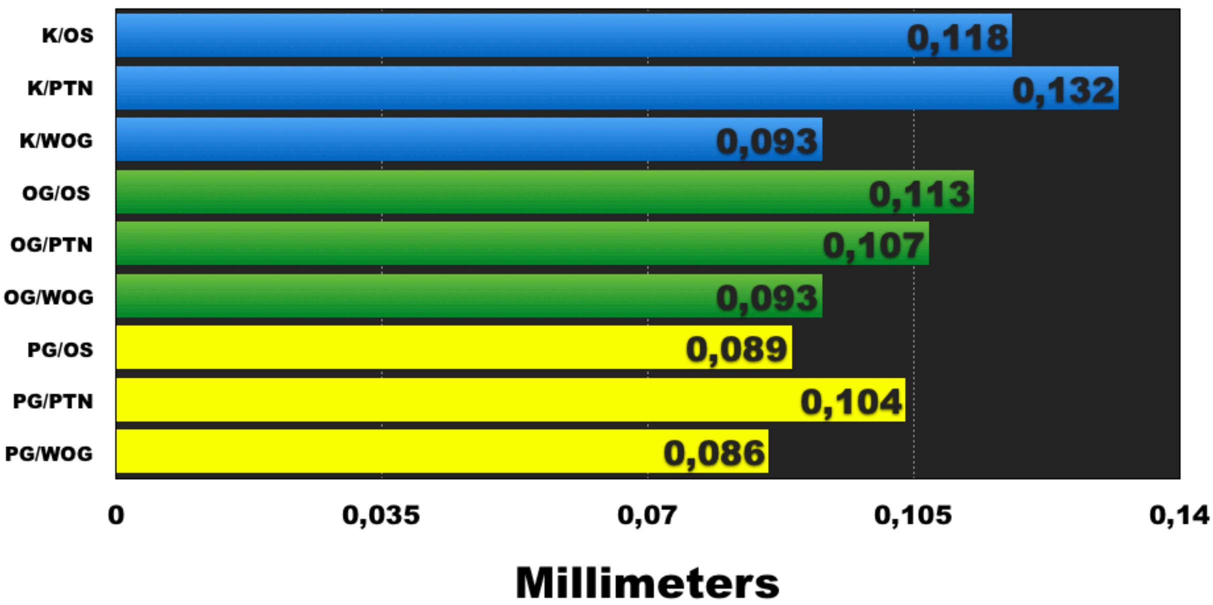

Figure 4.31. Mean canal transportation ratio values of shaping instruments in the middle third

The highest mean transportation value in the middle third was observed with the K/PTN group (0.132 ± 0.038 mm) and the lowest mean transportation value was recorded with the PG/WOG group (0.086 ± 0.020 mm). There were statistically significant differences between the mean transportation values of the following groups:

- The K/OS group compared to the K/WOG group (p=0.0202), the OG/WOG group (p=0.0208), the PG/OS group (p=0.0070), and the PG/WOG group (p=0.0032).

- The K/PTN group compared to the K/WOG group (p=0.0004), the OG/PTN group (p=0.0193), the OG/WOG group (p=0.0004), the PG/OS group (p<0.00012), the PG/PTN group (p=0.010), and the PG/WOG group (p<0.001).

- The OG/OS group compared to the PG/OS group (p=0.0279) and the PG/WOG group (p=0.0142).

Figure 4.32 is a representative sample from the K/PTN group that shows canal transportation and Figure 4.33 is a representative sample from the PG/WOG group that displays no canal transportation in the middle third of the root canals.

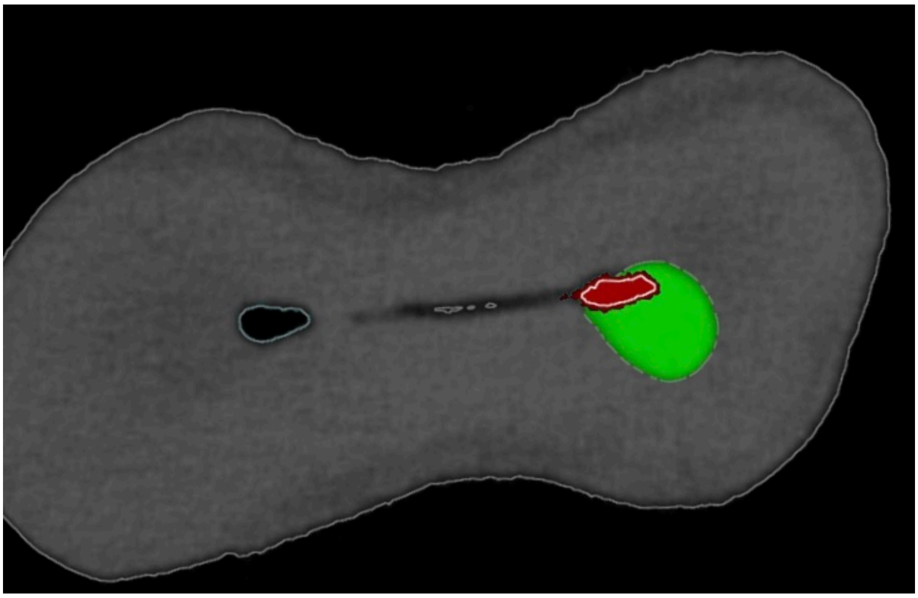

Figure 4.32: A representative sample from the K/PTN group that shows canal transportation at the middle third of the root canal (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument)

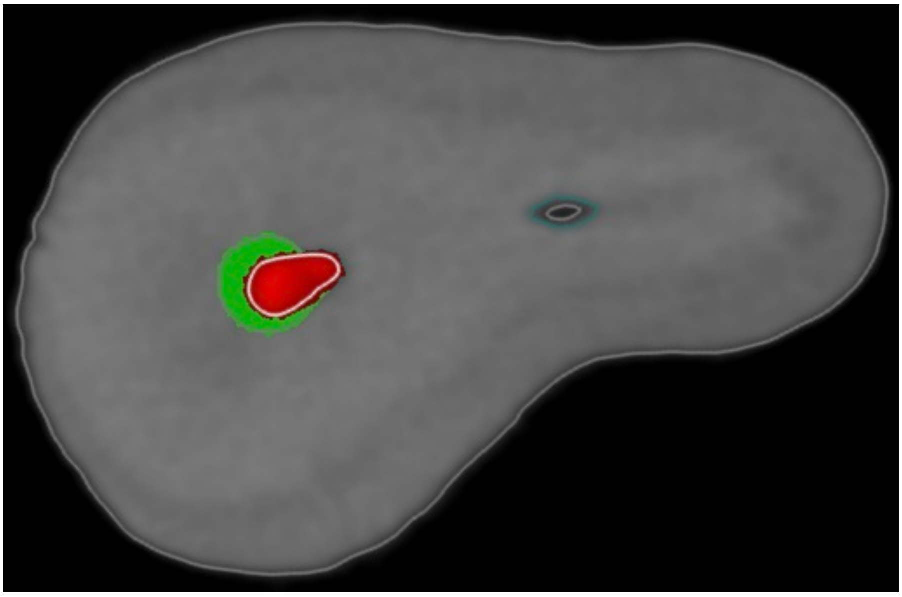

Figure 4.33: A representative sample from the PG/WOG group that displays no canal transportation at the middle third of the root canal (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument)

4.5.3. Canal Transportation Values of Shaping Instruments in the Coronal Third

Figure 4.34 depicts the mean transportation values of the glide path instruments at the apical third of the roots. The descriptive statistics are summarized in Table 4.16.

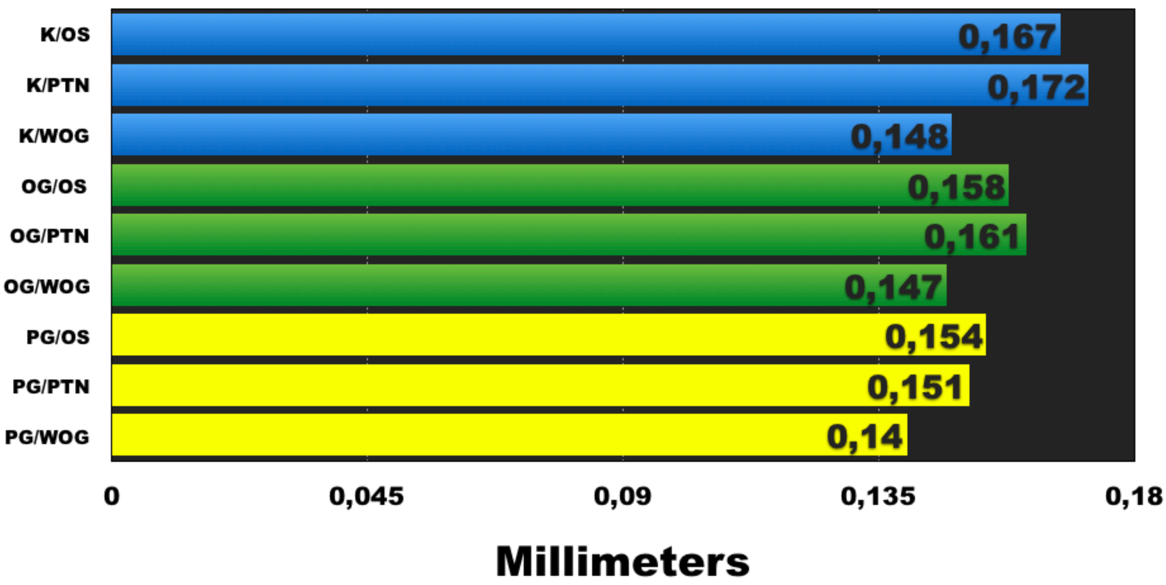

Figure 4.34: Mean canal transportation ratio values of shaping instruments in the coronal third

In the coronal third of the root, the highest mean transportation value was observed in the K/PTN group (0.172 ± 0.040 mm) and the lowest mean transportation value was recorded in the PG/WOG group (0.140 ± 0.027mm). There were statistically significant differences between the mean transportation values of the K/PTN group compared to the K/WOG group (p=0.0429), the OG/WOG group (p=0.0299), and the PG/WOG group (p=0.0066). Statistically significant differences were also found between the mean transportation values of the K/OS group compared to the PG/WOG group (p=0.0231).

Figure 4.35 is a representative sample from the K/PTN group that displays canal transportation and Figure 4.36 a representative sample from the PG/WOG group that shows no canal transportation in the coronal third of the root canals.

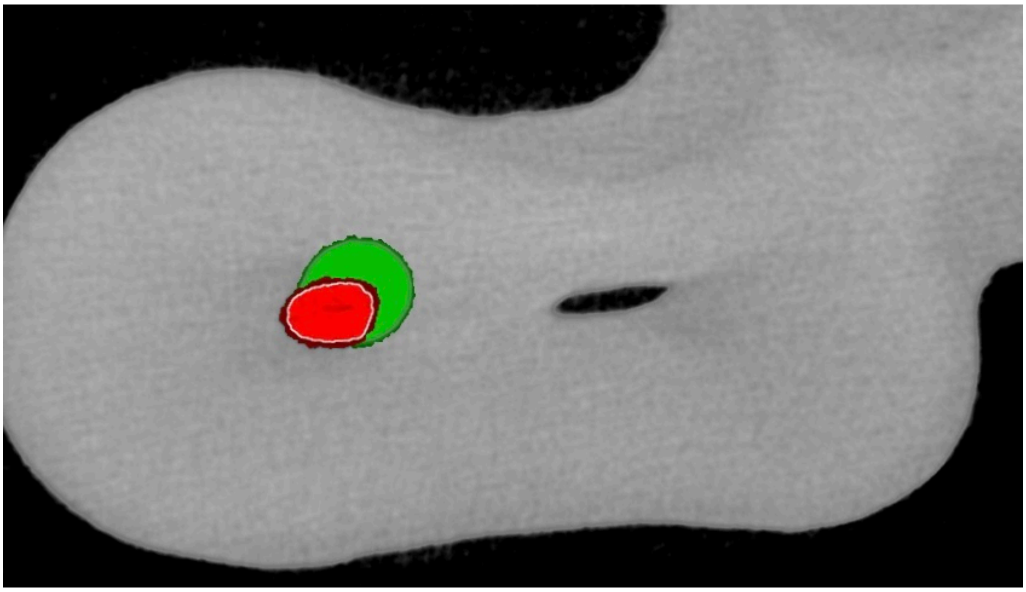

Figure 4.35: A representative sample from the K/PTN group that displays canal transportation at the coronal third of the root canal (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument)

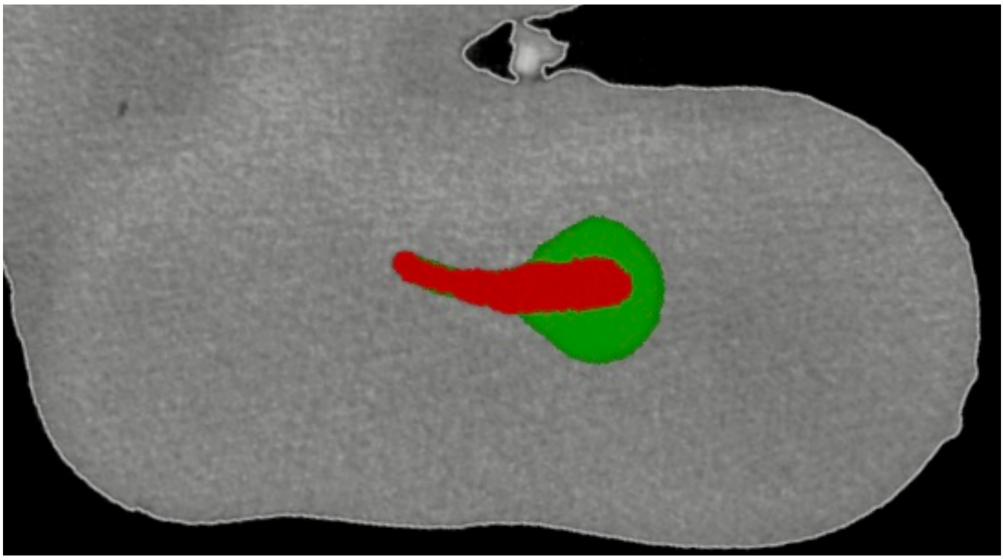

Figure 4.36: A representative sample from the PG/WOG group that shows no canal transportation at the coronal third of the root canal (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument)

4.5.4. Combined Canal Transportation Ratio Values of Glide Path Instruments

The combined results of the apical-, middle-, and coronal thirds for the mean canal transportation ratio values for each group after canal shaping are given in Figure 4.37 and Table 4.17.

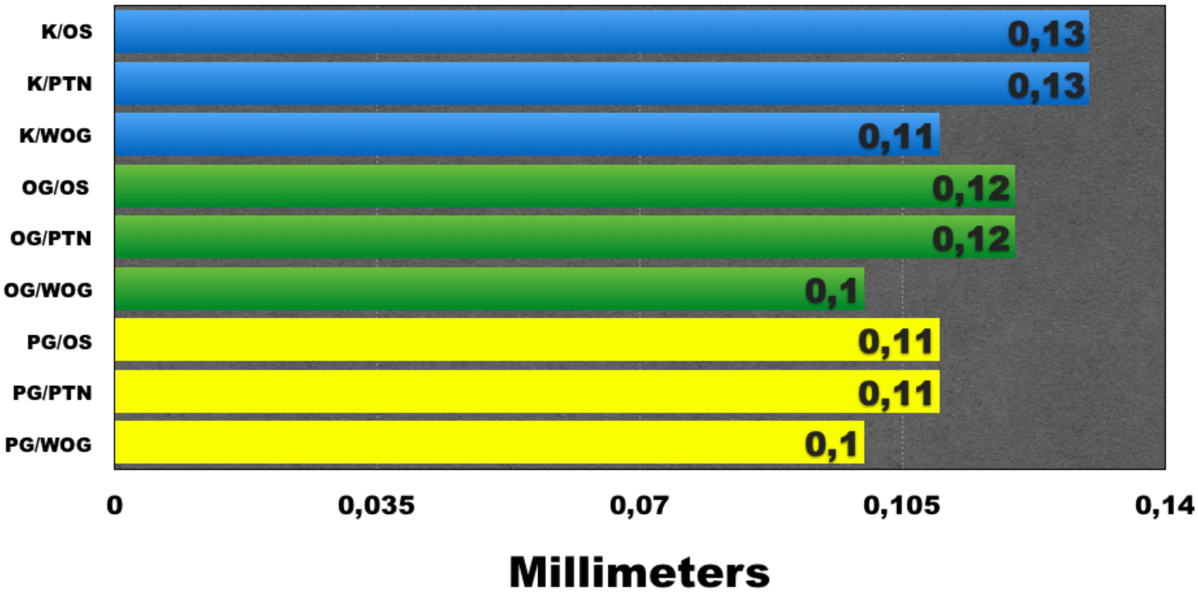

Figure 4.37: Combined mean canal transportation ratio values of shaping instruments

The best mean transportation ratio values were observed in OG/WOG (0.10 ± 0.043 mm) and in PG/WOG (0.10 ± 0.040 mm) and the worst mean centering ratio values were recorded with the K/OS group (0.13 ± 0.47 mm) and the K/PTN group (0.13 ± 0.48 mm). There were statistically significant differences between the mean transportation values of the following groups:

- The K/OS group compared to the K/WOG group (p=0.0079), the OG/WOG group (p=0.0019), the PG/OS group (p=0.0120) and the PG/WOG group (p=0.0002).

- The K/PTN group compared to the K/WOG group (p=0.0030), the OG/WOG group (p=0.0006), the PG/OS group (p=0.0040), the PG/PTN group (p=0.0252) and the PG/WOG group (p<0.001).

- The OG/OS group compared to the PG/WOG group (p=0.0208).

- The OG/PTN group compared to the PG/WOG group (p=0.0215).

4.6 Volume of Dentine Removed with Shaping Instruments

The data collected for the volume of dentine removed showed a parametric distribution. Therefore, one-way ANOVA was used to compare the groups. Figure 4.38 and Table 4.18 show the results and descriptive statistics of the mean volumes of dentine removed for each group.

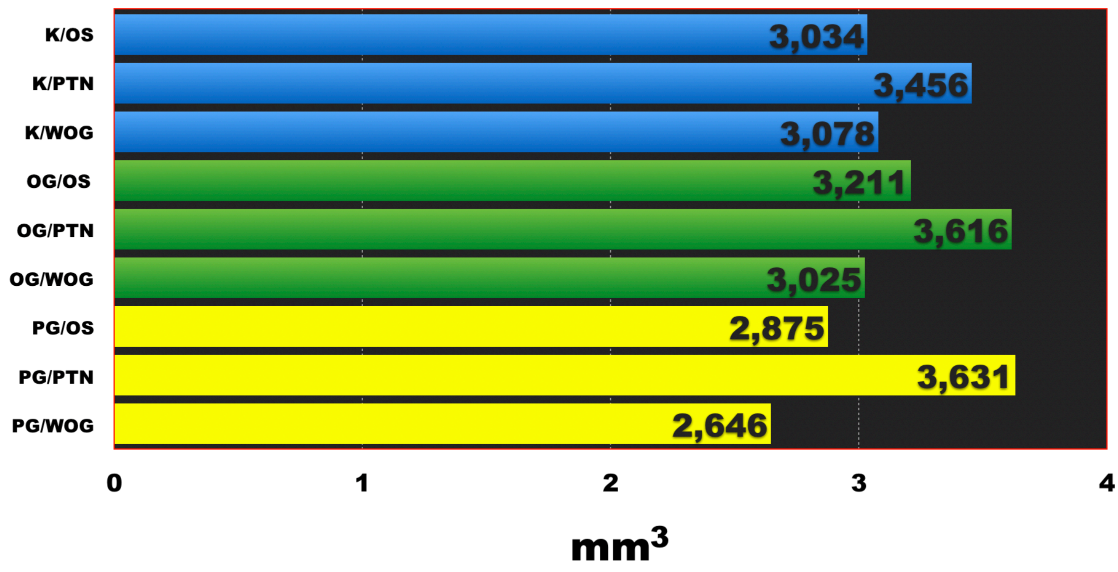

Figure 4.38: Mean volume of dentine removed with shaping instruments

The PG/WOG group showed the lowest mean volume of removed dentine (2,65 mm^3 ± 1.58 mm^3) and the PG/PTN group recorded the highest volume of removed dentine (3.63 mm^3 ± 1.67 mm^3). The one-way ANOVA indicated a statistical significant difference between the PG/WOG group compared to the PG/PTN (p=0.0272) group and the OG/PTN group (p<0.0295).

Figure 4.39 portrays representative 3D reconstructions of the mesio-buccal root canal volumes before instrumentation (red) and after canal preparation with the PG/PTN and the PG/WOG groups.

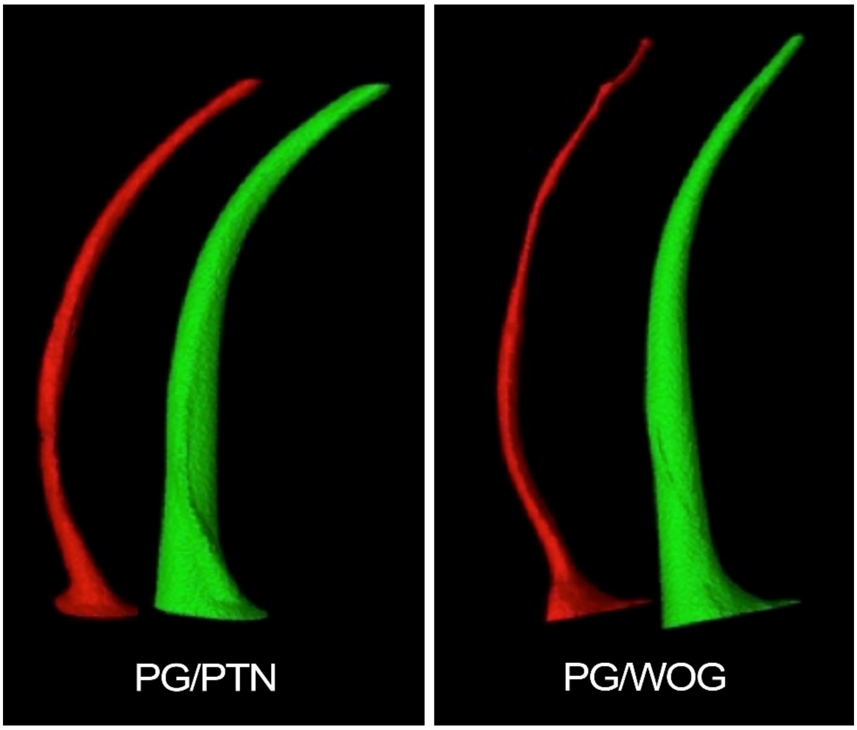

Figure 4.39: Representative 3D reconstructions of the bucco-lingual views of mesio-buccal root canal volumes before instrumentation and after canal preparation with PG/PTN and PG/WOG. (*Red* – pre-instrumentation volume; *green* – volume after canal preparation with shaping instrument(s))

4.7. Micro-computed tomography images displaying Canal Changes before, after Glide Path Preparation, and after Canal Preparation with Shaping Instruments

The representative 3D micro-computed tomography sample images (Figures 4.40-4.46) depict the changes in canal volume before and after glide path preparation, as well as before and after canal preparation with the shaping instruments of a mesio-buccal root canal of a maxillary first molar tooth. In addition, the sample images also display the superimposition of the canal systems and the changes of the canal axis at the apical- (2 mm), midroot- (5 mm) and coronal (9 mm) levels before and after glide path preparation, as well as before and after canal preparation with the shaping instruments.

Figures 4.40 and 4.41 display representative 3D micro-computed tomography images of a curved mesio-buccal root canal where the glide path was prepared with One G and the canal preparation done with the OneShape instrument, respectively.

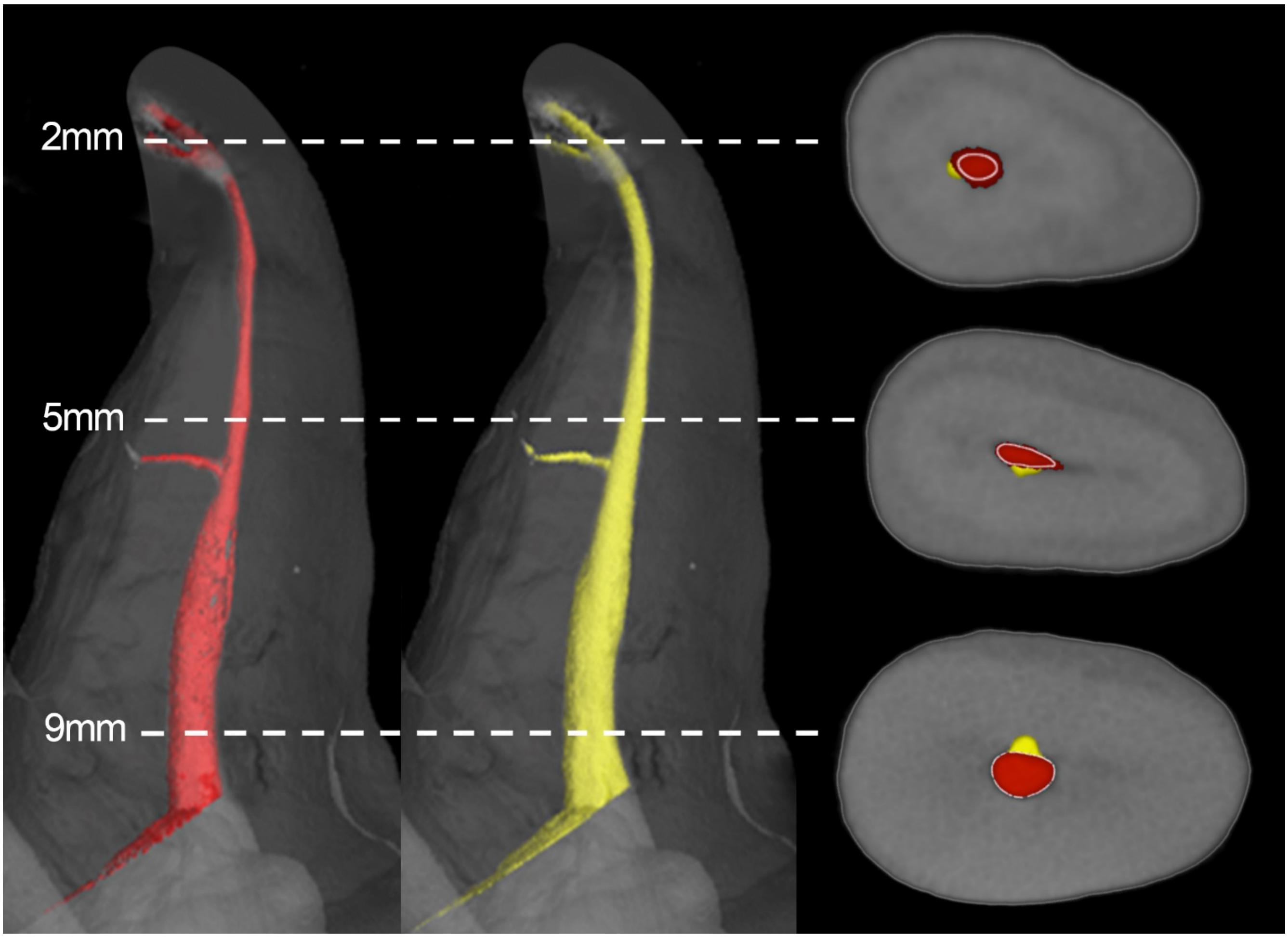

Figure 4.40: A representative sample of 3D images of a mesio-buccal root canal system: (a) pre-operative uninstrumented canal volume (*red);* (b) canal volume after glide path preparation with the One G instrument (*yellow);* (c) the superimposition of the canal systems and the changes of the canal axis before (*red*) and after (*yellow*) glide path preparation with the One G instrument at the apical-, midroot-, and coronal levels.

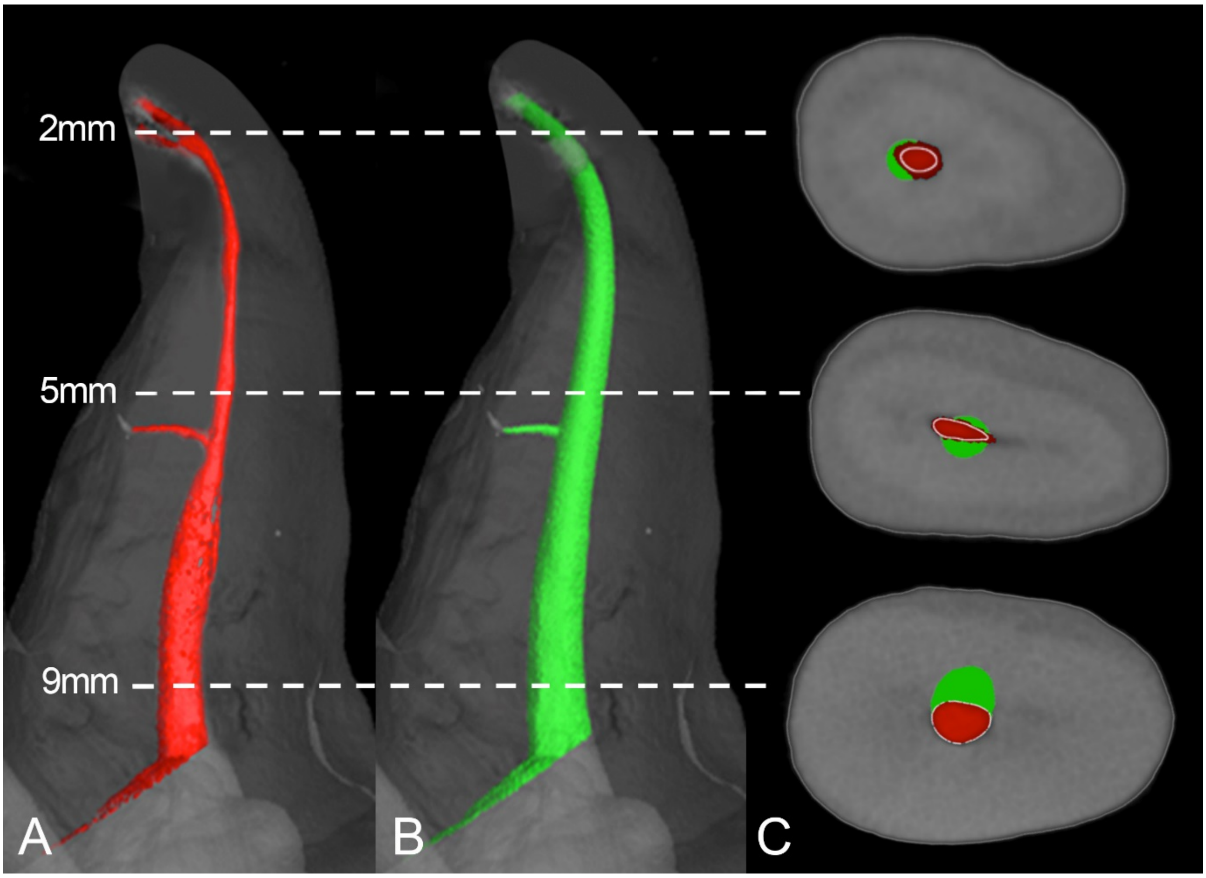

Figure 4.41: A representative sample of 3D images of a mesio-buccal root canal system: (a) pre-operative uninstrumented canal volume *(red);* (b) canal volume after canal preparation with the OneShape instrument (*green)*; (c) the superimposition of the canal systems and the changes of the canal axis before (*red*) and after canal preparation (*green*) with the OneShape instrument at the apical-, midroot-, and coronal levels

Representative 3D micro-CT images of a curved mesio-buccal root canal where the glide path was prepared with ProGlider and the canal preparation done with the ProTaper NEXT X1 and X2 instruments are portrayed in Figures 4.42 and 4.43, respectively.

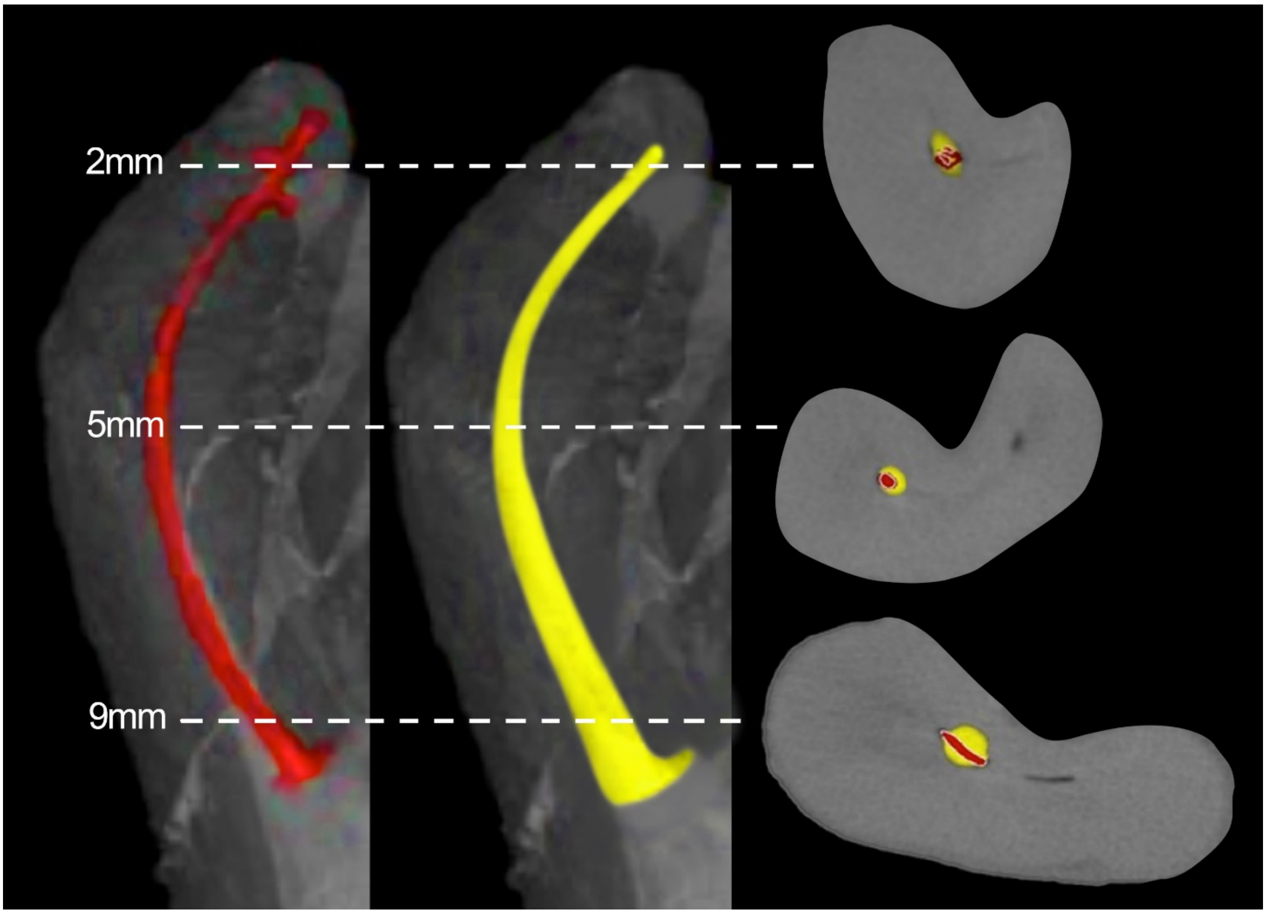

Figure 4.42: A representative sample of 3D images of a mesio-buccal root canal system: (a) pre-operative uninstrumented canal volume (*red);* (b) canal volume after glide path preparation with the ProGlider instrument (*yellow);* (c) the superimposition of the canal systems and the changes of the canal axis before (*red*) and after glide path preparation (*yellow*) with the ProGlider instrument at the apical-, midroot-, and coronal levels

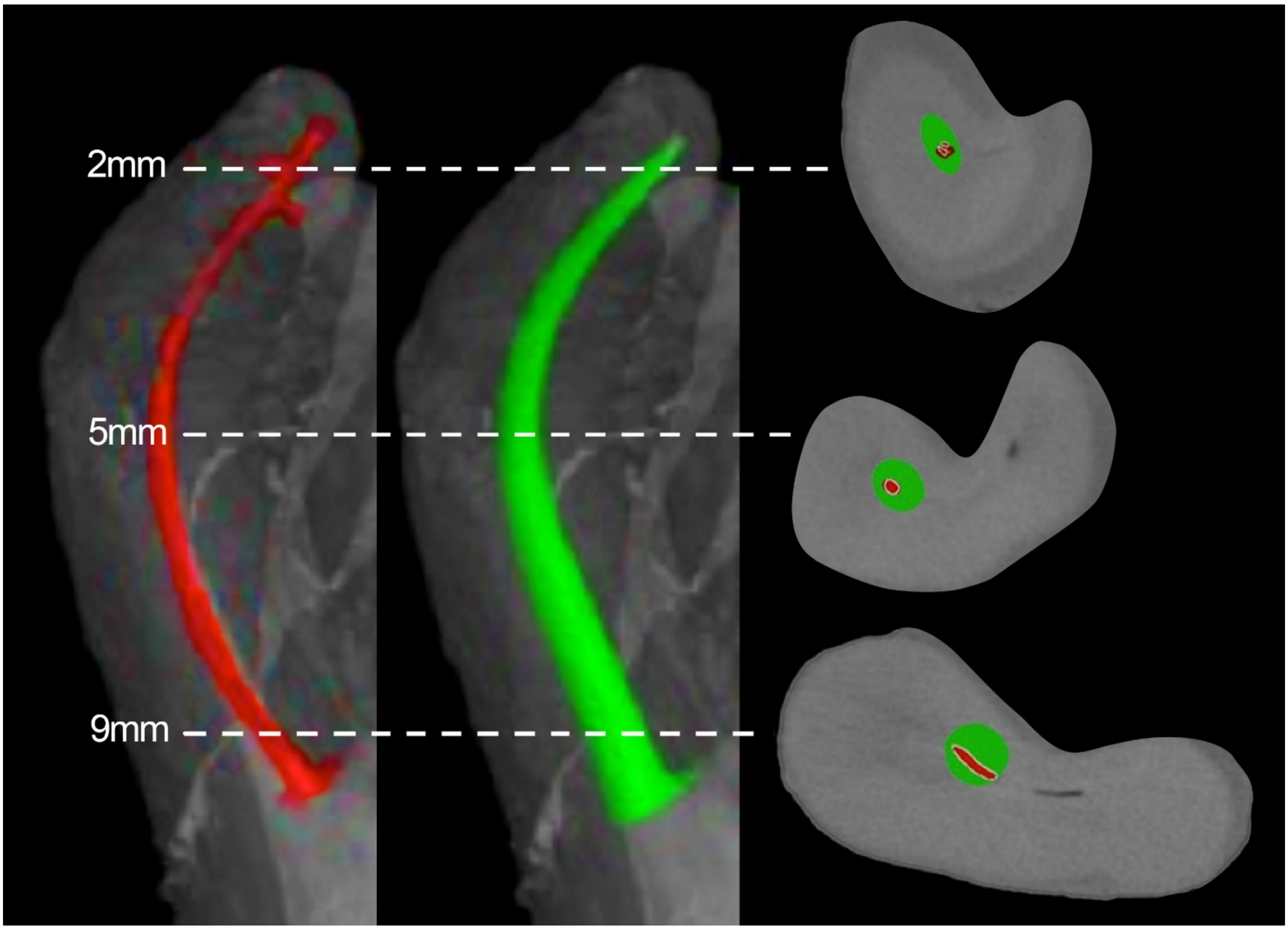

Figure 4.43: A representative sample of 3D images of a mesio-buccal root canal system: (a) pre-operative uninstrumented canal volume *(red); (b)* canal volume after canal preparation with the ProTaper NEXT X1 and X2 instruments (*green)*; (c) the superimposition of the canal systems and the changes of the canal axis before (*red*) and after canal preparation (*green*) with the ProTaper NEXT X1 and X2 instruments at the apical-, midroot-, and coronal levels

Figures 4.44 and 4.45 shows representative 3D micro-CT images of a "S-shaped" mesio-buccal root canal where the glide path was prepared with ProGlider and the canal preparation done with the Primary WaveOne Gold instrument, respectively.

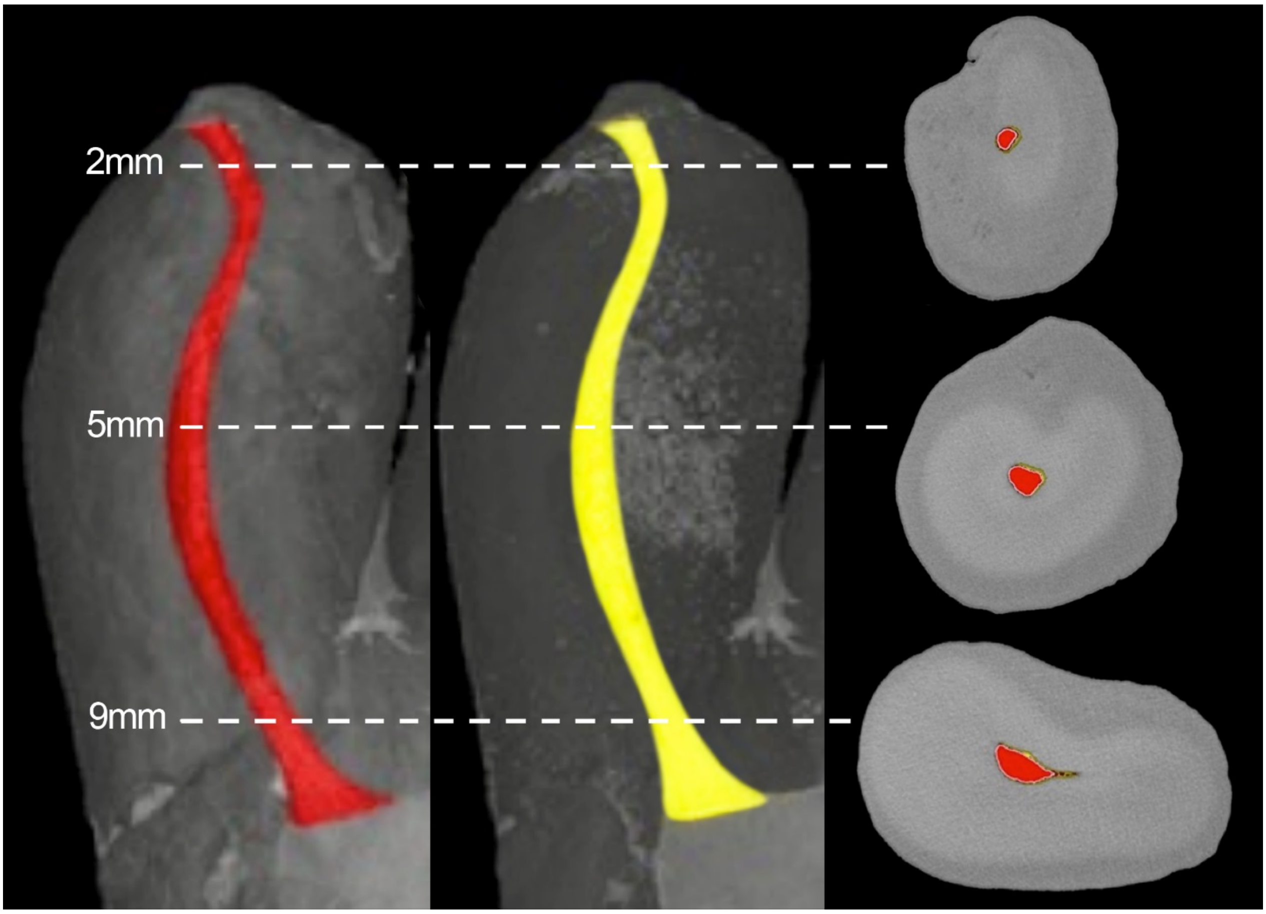

Figure 4.44: A representative sample of 3D images of a mesio-buccal root canal system: (a) pre-operative uninstrumented canal volume (*red);* (b) canal volume after glide path preparation with the ProGlider instrument (*yellow);* (c) the superimposition of the canal systems and the changes of the canal axis before (*red*) and after (*yellow*) glide path preparation with the ProGlider instrument at the apical-, midroot-, and coronal levels

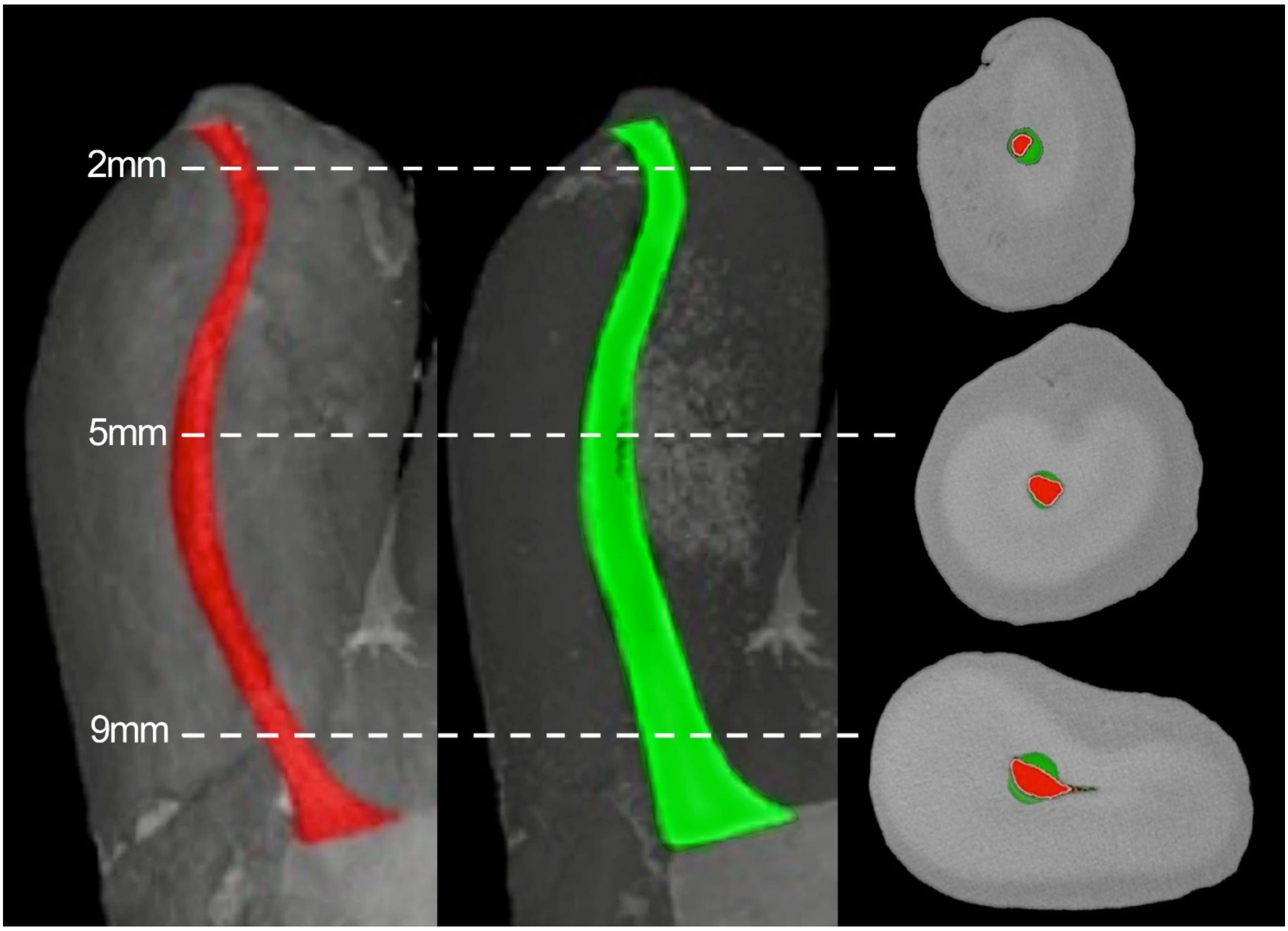

Figure 4.45: A representative sample of 3D images of a mesio-buccal root canal system: (a) pre-operative uninstrumented canal volume *(red)*; (b) canal volume after canal preparation with the Primary WaveOne Gold instrument (*green)*; (c) the superimposition of the canal systems and the changes of the canal axis before (*red*) and after (*green*) canal preparation with the Primary WaveOne Gold instrument at the apical-, midroot-, and coronal levels

Table 4.1. Descriptive statistics: Centering ratio values of glide path instruments in the apical third (n=45)

Preparation Method	**Mean**	**Standard Deviation**	**Minimum Value**	**Maximum Value**
K-Files	0.41 [a]	0.17	0.107	0.752
One G	0.61 [a]	0.13	0.335	0,947
ProGlider	0.66 [a]	0.17	0.243	0.999

Mean values with the same superscript letters were not statistically significantly different at $p<0.05$ using the one-way ANOVA test

Table 4.2. Descriptive statistics: Centering ratio values of glide path preparation instruments in the middle third (n=45)

Preparation Method	**Mean**	**Standard Deviation**	**Minimum Value**	**Maximum Value**
K-Files	0.32 [a]	0.16	0.112	0.775
One G	0.45 [b]	0.18	0.211	0,846
ProGlider	0.39 [b]	0.15	0.176	0.901

Mean values with the same superscript letters were not statistically significantly different at $p<0.05$ using the one-way ANOVA test

Table 4.3. Descriptive statistics: Centering ratio values of glide path preparation instrumentation the coronal third (n=45)

Preparation Method	Mean	Standard Deviation	Minimum Value	Maximum Value
K-Files	0.32 [a]	0.14	0.145	0.702
One G	0.39 [a]	0.20	0.112	0.845
ProGlider	0.43 [a]	0.15	0.213	0.812

Mean values with the same superscript letters were not statistically significantly different at $p<0.05$ using the one-way ANOVA test

Table 4.4. Descriptive statistics: Combined centering ratio values of glide path instruments (n=135)

Preparation Method	Mean	Standard Deviation	Minimum Value	Maximum Value
K-Files	0.35 [a]	0.16	0.107	0.775
One G	0.48 [b]	0.20	0.112	0,947
ProGlider	0.50 [b]	0.20	0.176	0.999

Mean values with the same superscript letters were not statistically significantly different at $p<0.05$ using the one-way ANOVA test

Table 4.5. Descriptive statistics: Canal transportation values (in mm) of glide path instruments in the apical third (n=45)

Preparation Method	**Median**	**Standard Deviation**	**Lower Quartile**	**Upper Quartile**
K-Files	0.075 [a]	0.03	0.067	0.087
One G	0.063 [b]	0.02	0.055	0,068
ProGlider	0.067 [b]	0.01	0.057	0.075

Mean values with the same superscript letters were not statistically significantly different at $p<0.05$ using the Kruskal-Wallis H test

Table 4.6. Descriptive statistics: Canal transportation values (in mm) of glide path instruments in the middle third (n=45)

Preparation Method	**Median**	**Standard Deviation**	**Lower Quartile**	**Upper Quartile**
K-Files	0.035 [a]	0.02	0.025	0.054
One G	0.031 [a]	0.01	0.023	0,038
ProGlider	0.029 [a]	0.02	0.022	0.043

Mean values with the same superscript letters were not statistically significantly different at $p<0.05$ using the Kruskal-Wallis H test

Table 4.7. Descriptive statistics: Canal transportation values (in mm) of glide path instruments in the coronal third (n=45)

Preparation Method	**Median**	**Standard Deviation**	**Lower Quartile**	**Upper Quartile**
K-Files	0.032 [a]	0.02	0.027	0.047
One G	0.031 [a]	0.01	0.025	0,035
ProGlider	0.030 [a]	0.02	0.024	0.037

Mean values with the same superscript letters were not statistically significantly different at $p<0.05$ using the Kruskal-Wallis H test

Table 4.8. Descriptive statistics: Combined canal transportation values (in mm) of glide path instruments (n=135)

Preparation Method	**Median**	**Standard Deviation**	**Lower Quartile**	**Upper Quartile**
K-Files	0.038 [a]	0.03	0.027	0.066
One G	0.034 [a]	0.02	0.025	0,056
ProGlider	0.035 [a]	0.02	0.0025	0.058

Mean values with the same superscript letters were not statistically significantly different at $p<0.05$ using the Kruskal-Wallis H test

Table 4.9. Descriptive statistics: Volume of dentine removed (in mm^3) with glide path instruments (n=45)

Preparation Method	Median	Standard Deviation	Lower Quartile	Upper Quartile
K-Files	0.528 [a]	0.28	0.344	0.631
One G	0.393 [a]	0.34	0.187	0.666
ProGlider	0.570 [a]	0.39	0.414	0.745

Mean values with the same superscript letters were not statistically significantly different at $p<0.05$ using the Kruskal-Wallis H test

Table 4.10. Descriptive statistics: Centering ratio values of shaping instruments in the apical third (n=15)

Shaping Method	Mean	Standard Deviation	Minimum Value	Maximum Value
K/OS	0.52 [a]	0.36	0.058	1.276
K/PTN	0.55 [a]	0.41	0.068	1.543
K/WOG	0.59 [a]	0.35	0.033	1.421
OG/OS	0.53 [a]	0.28	0.103	1.353
OG/PTN	0.56 [a]	0.33	0.068	1.167
OG/WOG	0.60 [a]	0.32	0.115	1.376
PG/OS	0.55 [a]	0.33	0.103	1.254
PG/PTN	0.60 [a]	0.32	0.144	1.334
PG/WOG	0.62 [a]	0.33	0.121	1.276

Mean values with the same superscript letters were not statistically significantly different at $p<0.05$ using the one-way ANOVA test

Table 4.11. Descriptive statistics: Centering ratio values of shaping instruments in the middle third (n=15)

Shaping Method	Mean	Standard Deviation	Minimum Value	Maximum Value
K/OS	0.49 [a]	0.29	0.002	1.178
K/PTN	0.45 [a]	0.34	0.082	1.275
K/WOG	0.43 [a]	0.30	0.125	1.415
OG/OS	0.44 [a]	0.25	0.076	1.043
OG/PTN	0.50 [a]	0.39	0.004	1.377
OG/WOG	0.45 [a]	0.29	0.122	1.328
PG/OS	0.54 [a]	0.35	0.002	1.271
PG/PTN	0.47 [a]	0.29	0.043	1.223
PG/WOG	0.44 [a]	0.29	0.136	1.279

Mean values with the same superscript letters were not statistically significantly different at $p<0.05$ using the one-way ANOVA test

Table 4.12. Descriptive statistics: Centering ratio values of shaping instruments in the coronal third (n=15)

Shaping Method	**Median**	**Standard Deviation**	**Lower Quartile**	**Upper Quartile**
K/OS	0.27	0.27	0.179	0.414
K/PTN	0.27	0.34	0.178	0.367
K/WOG	0.48	0.33	0.314	0.601
OG/OS	0.23	0.32	0.142	0.457
OG/PTN	0.32	0.29	0.146	0.467
OG/WOG	0.49 [b]	0.16	0.452	0.701
PG/OS	0.25 [c]	0.28	0.166	0.422
PG/PTN	0.35	0.34	0.281	0.521
PG/WOG	0.53 [a]	0.34	0.357	0.743

[a] Statistically significantly different from K/OS, K/PTN, OG/OS and PG/OS at $p<0.05$ using the Kruskal-Wallis H test

[b] Statistically significantly different from OG/OS at $p<0.05$ using the Kruskal-Wallis H test

[c] Statistically significantly different from OG/WOG at $p<0.05$ using the Kruskal-Wallis H test

Table 4.13. Descriptive statistics: Combined mean centering ratio of shaping instruments (n=45)

Shaping Method	Mean	Standard Deviation	Minimum Value	Maximum Value
K/OS	0.52 [a]	0.39	0.275	0.885
K/PTN	0.46 [a]	0.35	0.116	0.814
K/WOG	0.43 [a]	0.31	0.254	0.749
OG/OS	0.54 [a]	0.26	0.405	0.661
OG/PTN	0.48 [a]	0,34	0.155	0.800
OG/WOG	0.45 [a]	0.30	0.187	0.816
PG/OS	0.56 [a]	0.32	0.279	2.345
PG/PTN	0.53 [a]	0.34	0.120	0.854
PG/WOG	0.44 [a]	0.31	0.125	0.782

Mean values with the same superscript letters were not statistically significantly different at $p<0.05$ using the one-way ANOVA test

Table 4.14. Descriptive statistics: Canal transportation ratio values (in mm) of shaping instruments in the apical third (n=15)

Shaping Method	Mean	Standard Deviation	Minimum Value	Maximum Value
K/OS	0.107 [a]	0.046	0.035	0.219
K/PTN	0.096 [b]	0.033	0.030	0.168
K/WOG	0.078	0.025	0.037	0.128
OG/OS	0.083	0.020	0.054	0.128
OG/PTN	0.085 [c]	0.026	0.035	0.136
OG/WOG	0.068	0.026	0.022	1.126
PG/OS	0.081	0.020	0.041	0.127
PG/PTN	0.084	0.023	0.030	0.128
PG/WOG	0.065	0.026	0.040	0.136

[a] Statistically significantly different from K/WOG, OG/OS, OG/PTN, OG/WOG, PG/OS, PG/PTN and PG/WOG at $p<0.05$ using the one-way ANOVA test

[b] Statistically significantly different from K/WOG, OG/WOG and PG/WOG at $p<0.05$ using the one-way ANOVA test

[c] Statistically significantly different from PG/WOG at $p<0.05$ using the one-way ANOVA test

Table 4.15. Descriptive statistics: Canal transportation ratio values (in mm) of shaping instruments in the middle third (n=15)

Shaping Method	**Mean**	**Standard Deviation**	**Minimum Value**	**Maximum Value**
K/OS	0.118 [a]	0.036	0.036	0.174
K/PTN	0.132 [b]	0.038	0.050	0.219
K/WOG	0.093	0.021	0.053	0.128
OG/OS	0.113 [c]	0.027	0.060	0.162
OG/PTN	0.107	0.030	0.050	0.157
OG/WOG	0.093	0.027	0.049	1.127
PG/OS	0.089	0.023	0.052	0.151
PG/PTN	0.104	0.033	0.023	0.171
PG/WOG	0.086	0.020	0.054	0.120

[a] Statistically significantly different from K/WOG, OG/WOG, PG/OS and PG/WOG at $p<0.05$ using the one-way ANOVA test

[b] Statistically significantly different from K/WOG, OG/PTN, OG/WOG, PG/OS, PG/PTN and PG/WOG at $p<0.05$ using the one-way ANOVA test

[c] Statistically significantly different from PG/OS and PG/WOG at $p<0.05$ using the one-way ANOVA test

Table 4.16. Descriptive statistics: Canal transportation ratio values (in mm) of shaping instruments in the coronal third (n=15)

Shaping Method	**Mean**	**Standard Deviation**	**Minimum Value**	**Maximum Value**
K/OS	0.167 [a]	0.037	0.084	0.259
K/PTN	0.172 [b]	0.040	0.072	0.270
K/WOG	0.148	0.036	0.074	0.212
OG/OS	0.158	0.027	0.133	0.230
OG/PTN	0.161	0.032	0.127	0.250
OG/WOG	0.147	0.029	0.103	0.203
PG/OS	0.154	0.026	0.093	0.201
PG/PTN	0.151	0.030	0.091	0.221
PG/WOG	0.140	0.027	0.072	0.202

[a] Statistically significantly different from PG/WOG at $p<0.05$ using the one-way ANOVA test

[b] Statistically significantly different from K/WOG, OG/WOG and PG/WOG at $p<0.05$ using the one-way ANOVA test

Table 4.17. Descriptive statistics: Combined canal transportation ratio values (in mm) of shaping instruments (n=45)

Shaping Method	Mean	Standard Deviation	Minimum Value	Maximum Value
K/OS	0.13 [a]	0.047	0.035	0.259
K/PTN	0.13 [b]	0.048	0.030	0.270
K/WOG	0.11	0.041	0.037	0.212
OG/OS	0.12 [c]	0.039	0.054	0.230
OG/PTN	0.12 [d]	0.043	0.035	0.250
OG/WOG	0.10	0.043	0.022	0.203
PG/OS	0.11	0.040	0.041	0.201
PG/PTN	0.11	0.040	0.023	0.221
PG/WOG	0.10	0.040	0.040	0.202

[a] Statistically significantly different from K/WOG, OG/WOG, PG/OS and PG/WOG at $p<0.05$ using the one-way ANOVA test

[b] Statistically significantly different from K/WOG, OG/WOG, PG/OS, PG/PTN and PG/WOG at $p<0.05$ using the one-way ANOVA test

[c] Statistically significantly different from PG/WOG at $p<0.05$ using the one-way ANOVA test

[d] Statistically significantly different from PG/WOG at $p<0.05$ using the one-way ANOVA test

Table 4.18. Descriptive statistics: Volume of dentine removed (in mm^3) with shaping instruments (n=15)

Shaping Method	**Mean**	**Standard Deviation**	**Minimum Value**	**Maximum Value**
K/OS	3.034^{a}	0.903	2.053	5.629
K/PTN	3.456^{a}	1,394	2.013	6.581
K/WOG	3.078^{a}	0.567	1.882	3.822
OG/OS	3.211^{a}	1.263	1.672	5.346
OG/PTN	3.616^{b}	1.228	1.180	5.445
OG/WOG	3.025^{a}	1.097	1.453	5.342
PG/OS	2.875^{a}	0.772	1.692	4.274
PG/PTN	3.631^{b}	1.674	1.709	7.143
PG/WOG	2.646^{a}	1.518	1.027	5.755

Mean values with the same superscript letters were not statistically different at $p<0.05$

Chapter 5: Discussion

The aim of this study was to determine which of the glide path and root canal preparation technique combinations is best suited for the shaping of root canals after glide path preparation in curved root canals of extracted human maxillary molars using micro-computed tomography scanning. A combination of various glide path preparation instruments and shaping systems resulted in nine technique groups: Group K/OS (K-FlexoFile + OneShape); Group K/PTN (K-FlexoFile + ProTaper NEXT); Group K/WOG (K-FlexoFile + WaveOne Gold); OG/OS (One G + OneShape); OG/PTN (One G + ProTaper NEXT); OG/WOG (One G + WaveOne Gold); PG/OS (ProGlider + OneShape); PG/PTN (ProGlider + ProTaper NEXT); and PG/WOG (ProGlider + WaveOne Gold).

Various studies have shown that micro-computed tomography technology is an effective method for evaluating root canal preparation techniques. Micro computed tomography provides a non-destructive and easy-to-repeat method (Gambill, Alder and Del Rio, 1996; Nair and Nair, 2007). Data obtained with micro-computed tomography scans enable the identification of morphologic changes associated with different biomechanical preparations, including canal transportation, dentine removal, and final canal preparation (Peters et al. 2001; Loizides et al. 2007). A major advantage of micro-computed tomography scanning is the possibility of obtaining highly accurate evaluation of root canal shape by the superimposition and measurement of 3D renderings (Peters et al. 2001; Peters, 2004).

The mean canal centering ability and transportation values of the glide path and shaping instruments in this study were compared at levels 2 mm (apical), 5 mm (midroot), and 9 mm (coronal) from the anatomical apex of the tooth. These areas were chosen because they are particularly vulnerable to iatrogenic mishaps, especially in canals that are curved (Schneider, 1971; De-Oliveira Alves et al. 2012). The cutting edges of instruments typically press 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 dentine will be removed at the concavity, leading to canal transportation or straightening of varying degrees (Peters, 2004; Young, Parashos and Messer, 2007).

Biomechanical instrumentation of the root canal system during endodontic treatment is essential for eliminating apical periodontitis. Various combinations of instrumentation systems are used in the clinical setting. Contemporary engine-driven root-canal preparation techniques claim to facilitate safe and efficient preparations. The establishment of a reproducible glide path has been discussed at length in the literature. The maintenance of a glide path means having a smooth passage that can be reproduced by files used successively in the canal (Khatavkar and Hegde, 2010).

This smooth passage from the coronal orifice of the canal to the radiographic terminus or electronically determined portal of exit prior to root canal shaping has been recommended by a number of authors. The use of small hand files to confirm patency of the canal and to ensure sufficient space for rotary instruments to passively follow is advocated to ensure the safe use of engine-driven instruments (Blum et al. 2003). According to Bergmans et al. (2001) rotary instruments should not be used where a hand instrument has not been placed before. Owing to their extreme flexibility and non-end cutting tips, rotary NiTi files are not intended for initial negotiation of the root canal (Young, Parashos and Messer, 2007; Peters and Paqué, 2010).

In the present study, patency of each of the 135 canals was checked using a 08 K-FlexoFile. Forty–five canals were then prepared for glide path, with the use of only pre-curved stainless steel hand K-FlexoFiles. The results of this study show that the use of rotary glide-path enlargement systems outperformed glide path preparation with the use of manual hand K-File for both apical canal transportation and centering.

This study examined the centering ability, canal transportation and intra-canal volume changes after stainless steel K-FlexoFiles, One G and the ProGlider file had been used for glide path preparation in curved root canals of extracted human molars. The mean canal centering ability values of the glide path instruments were compared at levels 2 mm (apical), 5 mm (midroot), and 9 mm (coronal) from the anatomical apex of the tooth. The results of the present study were that glide path enlargement with stainless steel K-FlexoFiles was less centered than for One G and the ProGlider file at the apical level, midroot level, and coronal level. At all levels examined the mean centering ratios for the stainless steel K-FlexoFile group were statistically higher than for the NiTi rotary glide path file groups. Statistically similar observations were made for the One G and ProGlider groups at all levels examined.

These results are similar to those of other studies that compared the effects of glide path enlargement after K-Files and NiTi rotary glide path file systems had been used (Berutti et al. 2009; Pasqualini et al. 2012; Paleker and Van der Vyver, 2016). The recent study by Paleker and van der Vyver (2016) also made use of micro-computed tomography to examine glide path enlargement in curved canals. These researchers compared the use of G-Files and ProGlider files with stainless steel K-Files and concluded that these NiTi rotary glide path files have a high root canal centering ability, cause fewer modifications of the canal curvature and, therefore, fewer canal aberrations. This was in accordance with the results of the present study, which showed the superior centering ability of the NiTi rotary ProGlider and One G files over stainless steel K-FlexoFiles at all levels examined.

According to the Glossary of Endodontic Terms of the American Association of Endodontists, canal transportation is defined as follows: "Removal of canal wall structure on the outside curve in the apical half of the canal due to the tendency of files to restore themselves to their original linear shape during canal preparation; may lead to ledge formation and possible perforation" (American Association of Endodontists, 2012). The mean canal transportation values of the glide path instruments were compared at levels 2 mm (apical), 5 mm (midroot), and 9 mm (coronal) from the anatomical apex. The results of this study showed statistically similar canal transportation mean values for the all three groups at the midroot and coronal levels. At the apical level however, mean transportation values for stainless steel K-Files were statistically significantly more than both those of both One G and ProGlider. The two rotary glide path file groups exhibited statistically similar apical canal transportation values.

Previous studies have established that canal transportation causes inappropriate dentine removal, which leads potentially to straightening of the original canal curvature and the formation of ledges in dentine walls.

All endodontic instruments, regardless of the alloy used during manufacturing, tend to straighten themselves inside the root canal. 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 asymmetrical dentine removal (Peters, 2004; Young, Parashos and Messer, 2007). A number of studies have shown that NiTi rotary glide path file systems exhibit less apical canal transportation than stainless steel K-Files (Glosson et al. 1995; Tasdemir et al. 2005; Pasqualini et al. 2012; Paleker and Van der Vyver, 2016). The results for apical canal transportation in the present study confirm the results of these studies. A micro-computed tomography study by Moore, Fitz-Walter and Parashos (2009) examined apical canal transportation following glide path enlargement with stainless steel K-Files and NiTi rotary instruments. Undesired apical dentine removal by stainless steel instruments was concluded to be more pronounced in canals with more severe curvatures. A study by Pasqualini et al. (2012) reported similar findings for curved canals and concluded that that NiTi rotary glide path instruments were able to precisely prepare a canal to larger apical sizes with minimal risk of iatrogenic damage.

Stainless steel reamers, which should be used in a reaming working motion, cause marked transportation or straightening of the canal, especially in canals with ovoid cross-sections (Alodeh, Doller and Dummer, 1989; Schäfer, Tepel and Hoppe, 1995). Distinct transportation of curved canals was also a consistent finding for stainless steel K-Files with a rotational cutting action in combination with a longitudinal filing motion in other studies (Schäfer, Tepel and Hoppe, 1995; Lam et al. 1999). These undesirable effects can be explained by the flexural rigidity of the stainless steel material and inherent inability of all but the smallest stainless steel instruments to maintain the original canal curvature (Jafarzadeh and Abbott, 2007).

In addition to the canal anatomy, the cross-sectional design, design of the instrument tip and stiffness of the file have been identified as potential factors for preparation outcomes (Griffiths et al. 2001; Hülsmann, Herbst and Schäfers, 2003). In their study, Griffiths et al. (2001) reported a particularly high incidence of zips in acute apical curves associated with instruments with actively cutting tips. The ProGlider file has a square cross-section and is progressively tapered from 2% to 8% over its length. The One G instrument has a 3% taper with three cutting edges situated on three different radii relative to the canal axis. Both files have non-cutting tips that reduce the risk of ledge formation. The differences of the tip design between these files and stainless steel K-Files might be the main reason for the differences in the results presented in this study. Cross sectional design influences various factors that will affect the stress distribution, polar moment of inertia, depth of the flute, area of the continuous inner core and radial land and peripheral surface ground (Iqbal, Kohli and Kim, 2006).

The relative stiffness of stainless steel K-Files explain why these instruments exhibit a poor centering ability and higher apical canal transportation values in this study examining curved canals. In 1968, Craig, McIlwain and Peyton pointed out the complications presented by the use of rigid stainless steel files in curved canals. The performance of stainless steel K-Files might also be attributed to difference in the final apical preparation sizes among the three groups tested in this study. The final stainless steel K-File used for glide path enlargement was an ISO size 20, while ISO size 14 was used for One G and ISO size 16 for the ProGlider file. A study by Ajuz et al. (2013) suggested, however, that the final apical preparation size differences between the instruments examined could be irrelevant. The final apical preparation sizes in their study were either ISO size 19 or 20 for the stainless steel K-File and NiTi groups, yet the latter performed significantly better than the stainless steel K-File group. The results of the present study are similar to their findings where they concluded that canal deviations were more evident in the stainless steel K-File group.

The high flexibility of NiTi rotary instruments is related to the low modulus of elasticity and to the super-elastic behaviour of this alloy (Walia, Brantley and Gerstein, 1988). The latter is associated with the stress-induced martensitic transformation of austenitic phase to the B19' martensitic structure (Thompson, 2000). Appropriate choice of chemical composition and thermo-mechanical treatments applied during instrument manufacturing is required for this transformation to produce a large recoverable strain and thus render the instrument more flexible (Bahia et al. 2005; Miyai et al. 2006).

No statistically significant differences were shown in the volume of dentine removed between the glide-path instrument groups. The ProGlider group recorded the highest volume of removed dentine, followed by the K-File group and then the One G group.

The centering and transportation changes created by glide-path preparation instruments might be exacerbated during subsequent shaping. Through shaping, the long axis of a curved root canal will be displaced and in this way the angle of curvature will be decreased, which will result in the straightening of the original curvature of the canal. In the present study, no significant differences in the centering ability of the shaping groups were found in the apical and middle thirds of the canals. In the coronal third, however, PG/WOG performed statistically significantly better than K/OS, K/PTN, PG/OS and OG/OS, which exhibited the worst centering ratio at this level. Poorly centered techniques in the coronal third pose a risk of potential strip perforations in the furcation region. It is important to note that in spite of statistically inferior centering ratios exhibited by K-Files following the glide path examination, K-Files combined with WaveOne Gold K/WOG showed a statistically significantly superior centering ratio when compared with K/OS and K/PTN and, notably, OG/OS. These results suggest that WaveOne Gold is not affected by glide path outcomes and performs consistently well in regard to the centering ratio.

Canal transportation can cause procedural errors such as ledges, strip-perforations, and leakage at the apex (Peters, 2004). Additional consequences include are: extrusion of infected debris, with a risk of postoperative discomfort and excessive apical enlargement with an hourglass appearance; and subsequent defects in sealing (Jafarzadeh and Abbott, 2007; Loizides et al. 2007). Studies have shown that obturated root canals with irregular shapes leak significantly more compared with those with little or no canal transportation (Wu, Fan and Wesselink, 2000). Preservation of the original canal shape and the lack of canal aberrations are associated with superior antimicrobial activity and root canal sealing.

The occurrence of apical preparation errors has previously been linked to hand and rotary instruments with sharp tips (Powell, Simon and Maze, 1986; Griffiths, Bryant and Dummer, 2000). Research by Wu, Fan and Wesselink (2000) established that apical transportation greater than 0.300 mm may be detrimental to apical sealing during obturation. Apical canal transportation values in this study did not exceed 0.219 mm. The highest apical canal - transportation values were observed after shaping with OneShape and Protaper NEXT following glide path preparation with K-Files. Statistically, the highest mean transportation value was observed with K/OS group, followed by K/PTN. The lowest mean transportation value was recorded with PG/WOG group, which was statistically similar to each of K/WOG, OG/OS, OG/PTN, OG/WOG, PG/OS, and PG/PTN. Here, shaping outcomes appear to have been influenced by the glide path technique when OneShape and ProTaper NEXT were used after K-Files. WaveOne Gold groups, however, displayed consistently low apical transportation values in spite of the glide path technique used and the associated results.

The highest mid-canal transportation mean values were observed after shaping with OneShape and Protaper NEXT following glide path preparation with K-Files. The mean transportation value for the K/PTN group was statistically significantly higher than for all other groups. The lowest mean transportation value was recorded with the PG/WOG group, which was statistically similar to that of K/WOG, OG/WOG, and PG/OS. These groups exhibited statistically significantly lower transportation in the midroot than K/PTN, OG/OS, K/OS, PG/PTN, and OG/PTN. ProTaper NEXT displayed significantly high transportation values in the midroot irrespective of the glide path technique used. Mid root transportation results were even higher for OneShape, except when it was used after ProGlider. WaveOne Gold groups again displayed consistently low midroot transportation values regardless of the preceding glide path technique and results.

In the coronal third of the root, the highest mean transportation value was observed with in the K/PTN group. This value was significantly higher than for all other groups, followed by K/OS. The remaining groups displayed significantly less transportation at the coronal level, with the lowest mean value exhibited by the PG/WOG group. Here, shaping outcomes appear to have been influenced by the glide path technique when OneShape and ProTaper NEXT were used after K-Files. WaveOne Gold groups displayed consistently low coronal transportation values, however, in spite of the glide path technique used and the associated results.

A study by Saberi, Patel and Mannocci (2017) compared the centering ability and transportation of PTN, ProTaper Universal, RaCe 123 and Revo-S using micro-computed tomography. Results on transportation in the coronal third showed that PTN performed significantly better than ProTaper Universal. In the middle third, PTN and RaCe performed significantly better than ProTaper Universal and Revo-S. There was no significant difference between the four systems in the apical third. ProTaper NEXT prepared more centered root canal shapes when compared with RaCe, PTU and Revo-S. In the coronal and middle third of the root canals, centering for PTN was significantly better than for ProTaper Universal and Revo-S. ProTaper NEXT root canal preparations were more centered than those achieved with all other instruments in the apical third.

Results for transportation suggest that shaping outcomes were not significantly affected when WaveOne Gold was used after glide path preparation with K-Files. Coronal centering ratio and overall transportation results were consistently superior after WOG shaping following glide path enlargement with either ProGlider or One G. The significant difference between WOG groups and the two other shaping instruments can be explained by differences in working motion, cross-sectional design, and metallurgy.

Reciprocating files were developed to reduce the incidence of breakage of endodontic shaping files. These files are said to travel a shorter circumferential distance than a rotary instrument, which subjects the file to lower stress values

(Wan et al. 2011). These results were later confirmed by other studies (Pedullà et al. 2013; Vadhana et al. 2014). Adequate shaping ability of contemporary reciprocating files while preserving the original canal shape is a result of the interplay of three main factors: the reciprocation kinematics, the file cross-section, and the alloy type. Berutti et al. (2012a) found that WaveOne enhanced the canal centering ability with less modification of the canal curvature when compared with ProTaper. Another study demonstrated the remarkable centering ability of WaveOne regardless of the clinician's level of experience (Goldberg, Dahan and Machtou, 2012). Several studies have compared the shaping ability of reciprocating files with that of OneShape in moderate and severe canal curvatures (Bürklein, Benten and Schäfer, 2013; Saber, Nagy and Schäfer, 2015; Saleh et al. 2015). Dhingra et al. (2014) found that WaveOne maintained the original canal anatomy better and with less modification of the canal curvature compared with OneShape. Similar observations have been reported in other investigations (Tambe et al. 2014; Saber, Nagy and Schäfer, 2015).

A study by Hwang et al. (2014) used micro-computed tomography imaging to compare the shaping ability of Mtwo (VDW), a conventional NiTi file system, and Reciproc (VDW), a reciprocating file system morphologically similar to Mtwo. The authors used Mtwo in either a rotational or a reciprocating motion and found that no statistically significant differences existed between the three groups with respect to canal volume change. The use of Mtwo in a reciprocating motion exhibited similar results to those of Reciproc. However, when Mtwo was used in a continuous rotating motion, significantly more transportation occurred than when Mtwo used in a reciprocating motion. Hwang et al. (2014) concluded that Mtwo, a conventional rotary NiTi file system, might best be used in a reciprocating motion to improve its shaping ability.

Several factors such as cross-sectional design, chemical composition of the alloy, manufacturing techniques of endodontic instruments, and final preparation taper could have significant effects on the clinical performance of shaping file systems (Xu et al. 2006; Park et al. 2010). WaveOne Gold instruments have an alternating off-centered parallelogram-shaped cross-section design, PTN has an off-centered rectangular cross-sectional design, and OneShape is characterised by different cross-sectional designs over the entire length of the working part. In the tip region, the cross section of OneShape represents three cutting edges while the middle of the cross-sectional design progressively changes from a three-cutting-edge design to two cutting edges. It could be hypothesised that the off-centered parallelogram-shaped cross-section design of WaveOne Gold could enhance its torsional resistance and thereby its cutting performance.

It is worth noting that OneShape instruments are made of a conventional austenite 55-NiTi alloy, PTN instruments are made of M-Wire alloy and WaveOne Gold instruments are manufactured through the use of a gold heat-treatment technology. The manufacturer claims that the gold technology improves the flexibility and strength of the instrument (Dentsply Tulsa Dental Specialties, 2015b; Grande, Plotino and Ahmed, 2016). In addition, the M-Wire alloy from which the PTN instruments are manufactured has been reported as providing higher resistance to torsional stress than traditional NiTi rotary instruments (Kim et al. 2012; Wycoff and Berzins, 2012). This claim has been attributed to the small grain size of martensite noticed in M-Wire that improves torque strength and wear resistance (Ye and Gao, 2012). Gold heat treatment is performed manually by heating the instrument and then cooling slowly, contrary to the pre-manufacturing heat treatment of M-Wire technology. According to the manufacturer, this heat treatment enhances the elasticity of the instrument (Webber, 2015; Ozyurek, 2016). In addition, the greater flexibility of WaveOne Gold instruments could be due to the high Af temperatures and the two-stage specific transformation behaviour that improves the flexibility property (Ozyurek, 2016).

It is important for clinicians to be acquainted with the properties of different NiTi rotary systems and related implications for use relative to the clinical situations of root canals (Wycoff and Berzins, 2012). Torsional resistance and the flexibility properties of the instruments could be affected by the alloy from which the instrument is manufactured and its different cross-sectional design (Elsaka, Elnaghy and Badr, 2016).

In the present study, the final shaping size for all shaping systems was ISO 25 with taper sizes of 5% for OneShape, 6% for ProTaper NEXT, and 7% for WaveOne Gold. In spite of the final taper size, transportation values and coronal centering ration were consistently favourable for WaveOne Gold groups. The PG/WOG group showed the lowest mean volume of removed dentine and the PG/PTN group recorded the highest volume of removed dentine. High mean volumes of removed dentine were observed for all the PTN groups, regardless of the glide path enlargement technique. These results contrast with those of Pasqualini et al. (2015) who compared canals shaped with PG/PTN to those shaped with Bio-RaCe after glide path preparation with ScoutRaCe. The authors found that PG/PTN displayed superior preservation of canal anatomy. A similar study by Gagliardi et al. (2015) compared the shaping characteristics of the ProTaper Gold system (Dentsply/Sirona), ProTaper NEXT, and ProTaper Universal. These researchers concluded that both ProTaper Gold and ProTaper NEXT maintained more dentine than ProTaper Universal. The results of the current study could be attributed to the flexibility of the PTN M-Wire alloy and its off-centered rectangular cross section (Elnaghy and Elsaka, 2014). OneShape and WaveOne Gold resulted in lower volumes of dentine removed. These results might be explained by differences in the design of the instruments.

The CBCT study by Elnaghy and Elsaka (2014) compared the volume of removed dentine, transportation, and centering ability of PTN with and without glide path preparation. In this study glide paths were prepared with either PG or PathFile. Elnaghy and Elsaka found that there was no significant difference among the tested groups in the volume of removed dentine. However, PTN without a glide path showed a higher mean volume of removed dentine compared with the other tested groups. A study by Pereira et al. (2013) showed that PTN X2 is associated with a high torque. This study suggests that particular care be taken when X2 is used because this file may show considerable contact with the canal walls.

A 2014 study by Elnaghy and Elsaka reported that the creation of a glide path and preliminary enlargement enhances the performance of PTN instruments, whereas PTN without a glide path results in a higher mean volume of removed dentine. According to thos study, PG reduces the stress in PTN X1 and the pecking motions required during shaping because of its ability to create a preliminary flaring of the coronal and middle portions of the root canal. A recent study, however, examined the shaping outcomes of ProTaper NEXT after glide path preparation with manual K-File, PathFile, or ProGlider at the apical, coronal and level of maximum curvature (Alovisi et al. 2017). This study showed that canal volume and surface area variation were not different between groups after shaping with ProTaper NEXT X2 in spite of superior glide path enlargement volume changes exhibited by ProGlider. Alovisi et al. concluded that different glide path systems did not affect final preparation with respect to canal volume and surface area variation. Post-glide path analysis, however, revealed that the glide path instrument factor significantly affected shaping outcomes at the apical level for both the ratio of diameter ratios and the ratio of cross-sectional areas. Post-shaping analysis demonstrated a more centered preparation of ProGlider, compared with PathFile and K-Files, with a significantly reduced centre of gravity shift at the apical-, coronal-, and level of maximum curvature points of analysis. Elnaghy and Elsaka (2014) performed a similar study, which examined outcomes after glide path enlargement but showed that ProGlider seemed to improve ProTaper NEXT performance by positively influencing geometrical-shaping outcomes. It is important to note that K-Files were not included as a glide path preparation technique in this study. In the ProGlider group, the centre of gravity shift after shaping with ProTaper NEXT at the same three levels of analysis was lower than PathFile and K-File. They concluded that a glide path preserving the original canal anatomy, with fewer canal aberrations and the lowest variation in canal geometry and centering, particularly at the apical level, might provide more favourable conditions for the subsequent shaping phase.

In the present study, the increased canal volume after glide path preparation was statistically similar for the three groups compared. The present findings are in keeping with those of a previous study that reported similar volume increases during glide path management with PathFiles and the ProGlider instrument (Kirchhoff et al. 2015). The benefits of mechanical glide path enlargement have been shown in various studies (Berutti et al. 2009; Pasqualini et al. *2012*). According to De-Oliveira Alves et al. (2012) however, there are no demonstrable differences between manual and rotary glide path techniques. These findings are consistent with those of Bürklein and Schäfer (2013) who consider both techniques clinically reliable. They compared a manual- and a mechanical glide path with PathFiles and found no statistically significant differences. Bürklein and Schäfer concluded that centering ratio and canal transportation effects of glide path preparation with K-Files are not significantly exacerbated by shaping. The authors suggest that manual glide path with stainless steel K-Files should still be considered a valid technique when compared with NiTi rotary glide path systems. In this study, however, shaping outcomes were indeed affected by glide path preparation. Results show significantly increased transportation at all levels when the rotary shaping systems were used after glide path preparation with K-Files. Results were similar when the centering ratios were assessed at the coronal level. Results were, however, more favourable after reciprocation with WaveOne Gold following any one of the three glide path preparation techniques.

In considering these results, it is important to recognise the possible sources of error in micro-computed tomography scanning to avoid over interpretation of three-dimensionally reconstructed images (Mol, 1999). According to Endal et al. (2011) around 20 μm to 40 μm of dentine must be removed before a change in surface area can be registered. The segmentation process in itself tends to overemphasise the sharp edge for the root canal. This means that if a canal extension or isthmus is smaller than the resolving power of the scanner, no canal will be seen in the reconstructed image. Furthermore, surface details will appear sharper in the image than in reality (Davis and Wong, 1996). All of these potential errors call for cautious interpretation of quantitative assessment reports based on three-dimensionally reconstructed images (Mol, 1999).

Within the limitations of this study, WaveOne Gold resulted in less transportation and greater ability to maintain dentine thickness than the other shaping groups, irrespective of the glide path technique used.

Chapter 6: Conclusions

Within the limitations of the present study the conclusions that follow can be made:

Glide Path Preparation – Centering Ability

1. Both rotary NiTi glide path enlargement files (One G and ProGlider) displayed statistically significantly better mean centering ratios at the apical, midroot, and coronal levels than stainless steel K-FlexoFiles ($p<0.05$).

2. The mean combined centering ratios after glide path preparation showed a statistically significant difference between the mean centering ratio values of the two NiTi glide path enlargement files.

Glide Path Preparation – Transportation

1. Apical canal transportation ratio values after glide path enlargement were significantly higher for the K-FlexoFile group compared to the two NiTi glide path enlargement files ($p<0.05$), which were statistically similar ($p>0.05$) to each other.

2. Canal transportation ratio values at the midroot and coronal levels were statistically similar for all glide path groups ($p>0.05$).

Glide Path Preparation – Volume of Dentine Removed

1. There were no statistically significant differences among the three glide path groups regarding the volume of dentine removed ($p>0.05$).

Shaping Instruments – Centering Ability

1. No statistically significant difference was found in the mean centering ratios at the apical and midroot levels of the various glide path groups in combination with the shaping instruments ($p>0.05$).

2. Centering ratio results following glide path preparation with K-FlexoFile appeared to affect shaping outcomes at the coronal level for both PTN and OS groups. Here, K/WOG performed statistically significantly better than K/PTN and K/OS ($p<0.05$), which suggests that WOG compensated for the poor centering performance of K-FlexoFile glide path preparation.

3. At the coronal level the centering ratios of PG/WOG and OG/WOG were significantly better than for K/PTN, K/OS, OG/OS, and PG/OS groups ($p<0.05$). OneShape performed poorly following all glide path techniques with OG/OS and significantly displayed the worst centering ratio at this level. These results show that OneShape results in poorly centered preparations at the coronal level, regardless of the glide path technique used.

4. The mean combined centering ratio values of the various glide path groups in combination with the shaping instruments showed that

there were no statistically significant differences between the different combination groups (p>0.05).

Shaping Instruments Transportation

1. Apical canal transportation after shaping was significantly highest for K/OS followed by K/PTN. Transportation outcomes of K-FlexoFiles at the apical level were exacerbated after shaping with PTN and OS. Results at this level were statistically similar for the remaining groups (p>0.05). Here, the PG/WOG group exhibited the least transportation and the favourable results of the K/WOG group suggest that WOG compensated for the poor centering performance of K-FlexoFile glide path preparation.

2. Canal transportation at the midroot level was significantly higher for K/PTN than K/OS and OG/OS, which were statistically similar to each other. The combination of One G and OneShape showed poor transportation results at this level. The rest of the groups performed more favourably, with the PG/WOG group displaying the best results. Prior glide path preparation with K-FlexoFiles appeared to affect transportation outcomes at this level for both PTN and OS groups. Here, the K/WOG group performed statistically significantly better than K/PTN and K/OS (p<0.05), which suggests that WOG compensated for the poor centering performance of K-FlexoFile glide path preparation.

3. Coronal canal transportation after shaping was significantly highest for K/PTN followed by K/OS, in spite of favourable coronal glide path transportation results of K-FlexoFile. Statistically, the best results at this

level were observed in the K/WOG, OG/WOG, PG/WOG groups. Here the PG/WOG group exhibited the least transportation.

Shaping Instruments – Volume of Dentine Removed

1. The three groups for which ProTaper NEXT was used as a shaping instrument exhibited the highest volume of dentine removed with the highest volume removed by the PG/PTN group. Statistically, the lowest mean volume of removed dentine was displayed by the PG/WOG group, and the PG/PTN group recorded the highest volume of removed dentine. The only statistically significant differences occurred between PG/WOG compared to PG/PTN and OG/PTN groups ($p<0.05$).

The null/hypothesis is therefore rejected.

Chapter 7: References

Abou-Rass M, Frank AL and Glick DH (1980) The Anticurvature Filing Method to Prepare the Curved Root Canal. *The Journal of the American Dental Association,* 101(5): 792–794.

Ajuz NCC, Armada L, Gonçalves LS, Debelian G and Siqueira JF (2013) Glide Path Preparation in S-Shaped Canals with Rotary Pathfinding Nickel-Titanium Instruments. *Journal of Endodontics*, 39(4): 534–537.

Al-Hadlaq SMS, AlJarbou FA and AlThumairy RI (2010) Evaluation of Cyclic Flexural Fatigue of M-Wire Nickel-Titanium Rotary Instruments. *Journal of Endodontics*, 36(2): 305–307.

Al-Omari MAO and Dummer PMH (1995) Canal Blockage and Debris Extrusion with Eight Preparation Techniques. *Journal of Endodontics*, 21: 154–8.

Alattar S, Nehme W and Diemer F (2015) The Influence of Brushing Motion on the Cutting Behavior of 3 Reciprocating Files in Oval-Shaped Canals. *Journal of Endodontics*, 41(5): 703–709.

Allam CR (1996) Treatment of Stripping Perforations. *Journal of Endodontics*, 22: 699–702.

Alodeh MHA, Doller R and Dummer PMH (1989) Shaping of Simulated Root Canals in Resin Blocks Using the Step-Back Technique with K-Files Manipulated in a Simple In/out Motion. *International Endodontic Journal*, 22: 107–117.

Alovisi M, Cemenasco A, Mancini L, Paolino D, Scotti N, Bianchi CC and Pasqualini D (2017) Micro-CT Evaluation of Several Glide Path Techniques and ProTaper Next Shaping Outcomes in Maxillary First Molar Curved Canals. *International Endodontic Journal*, 50(4): 387–397.

American Association of Endodontists (2012) Glossary of Endodontic Terms. available at http://www.aae.org/publications-and-research/glossaries-and-guides/glossaries---guides.aspx

Ammon D, Shotton V, Gao Y and Maxwell R (2014) Endodontic Instruments and Methods of Manufacturing Thereof.

Bahia MGA, Martins RC, Gonzalez BM and Buono VTL (2005) Physical and Mechanical Characterization and the Influence of Cyclic Loading on the Behaviour of Nickel-Titanium Wires Employed in the Manufacture of Rotary Endodontic Instruments. *International Endodontic Journal*, 38: 795– 801.

Bergmans L, Van Cleyenbreugel J, Wevers M and Lambrechts P (2001) Mechanical Root Canal Preparation with NiTi Rotary Instruments: Rationale, Performance and Safety—status Report for the American Journal of Dentistry. *American Journal of Dentistry*, 14: 324–33.

Berutti E, Alovisi M, Pastorelli MA, Chiandussi G, Scotti N and Pasqualini D (2014) Energy Consumption of ProTaper Next X1 after Glide Path with and PathFiles and ProGlider. *Journal of Endodontics*, 40: 2015–8.

Berutti E, Cantatore G, Castellucci A, Chiandussi G, Pera F, Migliaretti G and Pasqualini D (2009), Use of Nickel-Titanium Rotary PathFile to Create the Glide Path: Comparison with Manual Preflaring in Simulated Root Canals. *Journal of Endodontics*, 35(3): 408–412.

Berutti E and Castellucci A (2009) Cleaning and Shaping of the Root Canal System. *Endodontics*, 2(IL Tridente, Florence, Italy).

Berutti E, Chiandussi G, Gaviglio I and Ibba A (2003) Comparative Analysis of Torsional and Bending Stresses in Two Mathematical Models of Nickel-Titanium Rotary Instruments: ProTaper versus ProFile. *Journal of Endodontics*, 29: 15–9.

Berutti E, Chiandussi G, Paolino DS, Scotti N, Cantatore G, Castellucci A and Pasqualini D (2012a) Canal Shaping with WaveOne Primary Reciprocating Files and ProTaper System: A Comparative Study. *Journal of Endodontics*, 38: 505–9.

Berutti E, Negro AR, Lendini M and Pasqualini D (2004) Influence of Manual Preflaring and Torque on the Failure Rate of ProTaper Rotary Instruments. *Journal of Endodontics*, 30(4): 228–230.

Berutti E, Paolino DS, Chiandussi G, Alovisi M, Cantatore G, Castellucci A and Pasqualini D (2012b) Root Canal Anatomy Preservation of WaveOne Reciprocating Files with or without Glide Path. *Journal of Endodontics*, 38(1): 101–4.

Blum JY, Cohen P, Machtou P and Micallef JP (1999) Analysis of Forces Developed during Mechanical Preparation of Extracted Teeth Using ProFile NiTi Rotary Instruments. *International Endodontic Journal*, 32: 24–31.

Blum JY, Machtou P, Ruddle CJ and Micallef JP (2003) The Analysis of Mechanical Preparations in Extracted Teeth Using Protaper Rotary Instruments: Value of the Safety Quotient. *Journal of Endodontics*, 29: 567–75.

Bortoluzzi EA, Carlon D Jr, Meghil MM, El-Awady AR, Niu L, Bergeron BE, Susin L, Cutler CW, Pashley DH and Tay FR (2015) Efficacy of 3D Conforming Nickel Titanium Rotary Instruments in Eliminating Canal Wall Bacteria from Oval-Shaped Root Canals. *Journal of Dentistry*, 43: 597–604.

Braga LC, Silva AC, Buono VT and Bahia MG (2014) Impact of Heat Treatments on the Fatigue Resistance of Different Rotary Nickel-Titanium Instruments. *Journal of Endodontics*, 40: 1494–7.

Bramante CM, Berbert A and Borges RP (1987) A Methodology for Evaluation of Root Canal Instrumentation. *Journal of Endodontics*, 13: 243–5.

Bryant ST, Thompson SA, Al-Omari MA and Dummer PM (1998) Shaping Ability of Profile Rotary Nickel-Titanium Instruments with ISO Sized Tips in Simulated Root Canals: Part 1. *International Endodontic Journal*, 31: 275–81.

Buchanan LS (2000) The Standardized-Taper Root Canal Preparation—Part 1. Concepts for Variably Tapered Shaping Instruments. *International Endodontic Journal*, 33: 516–29.

Bürklein S, Benten S and Schäfer E (2013) Shaping Ability of Different Single-File Systems in Severely Curved Root Canals of Extracted Teeth. *International Endodontic Journal*, 46(6): 590–7.

Bürklein S, Hinschitza K, Dammaschke T and Schäfer E (2012) Shaping Ability and Cleaning Effectiveness of Two Single-File Systems in Severely Curved Root Canals of Extracted Teeth: Reciproc and WaveOne versus Mtwo and ProTaper. *International Endodontic Journal*, 45: 449–61.

Bürklein S and Schäfer E (2006) The Influence of Various Automated Devices on the Shaping Ability of Mtwo Rotary Nickel-Titanium Instruments. *International Endodontic Journal*, 39: 945–51.

Bürklein S and Schäfer E (2012) Apically Extruded Debris with Reciprocating Single-File and Full Sequence Rotary Instrumentation Systems. *Journal of Endodontics*, 38: 850–2.

Bürklein S and Schäfer E (2013) Critical Evaluation of Root Canal Transportation by Instrumentation. *Endodontic Topics*, 29: 110–24.

Busquim S, Cunha RS, Freire L, Gavini G, Machado ME and Santos M (2015) A Micro-Computed Tomography Evaluation of Long-Oval Canal Preparation Using Reciprocating or Rotary Systems. *International Endodontic Journal*, 48: 1001–6.

Capar ID, Ertas H, Ok E, Arslan H and Ertas ET (2014) Comparative Study of Different Novel Nickel-Titanium Rotary Systems for Root Canal Preparation in Severely Curved Root Canals. *Journal of Endodontics*, 40(6): 852–6.

Cassim I and Van der Vyver PJ (2013) The Importance of Glide Path Preparation in Endodontics : A Consideration of Instruments and Literature. *South African Dental Journal*, 68(7): 322–7.

Cheung GSP (2007) Instrument Fracture: Mechanisms, Removal of Fragments, and Clinical Outcomes. *Endodontic Topics*, 16: 1–26.

Cheung GS and Liu CS (2009) A Retrospective Study of Endodontic Treatment outcome between Nickel-Titanium Rotary and Stainless Steel Hand Filing Techniques. *Journal of Endodontics,* 35(7): 938–943.

Craig RG, McIlwain ED and Peyton FA (1968) Bending and Torsion Properties of Endodontic Instruments. *Oral Surgery Oral Medicine Oral Pathology Oral Radiology and Endodontology*, 25: 239–254.

D'Amario M, Baldi M, Petricca R, De Angelis F, El Abed R and D'Arcangelo C (2013) Evaluation of a New Nickel-Titanium System to Create the Glide Path in Root Canal Preparation of Curved Canals. *Journal of Endodontics*, 39(12): 1581–4.

Da-Silva Limoeiro AG, Dos Santos AHB, De Martin AS, Kato AS, Fontana CE, Gavini G, Freire LG and Da Silveira Bueno CE (2016) Micro-Computed Tomographic Evaluation of 2 Nickel-Titanium Instrument Systems in Shaping Root Canals. *Journal of Endodontics*, 42(3): 496–9.

Davis GR and Wong FS (1996) X-Ray Microtomography of Bones and Teeth. *Physiological Measurement*, 17: 121–46.

De-Deus G, Arruda TE, Souza EM, Neves A, Magalhães K, Thuanne E and Fidel RA (2013) The Ability of the Reciproc R25 Instrument to Reach the Full Root Canal Working Length without a Glide Path. *International Endodontic Journal*, 46: 993–8.

De-Deus G, Belladonna FG, Souza EM, Silva EJNL, Neves ADE, Alves H, Lopes RT and Versiani MA (2015) Micro-Computed Tomographic Assessment on the Effect of ProTaper Next and Twisted File Adaptive Systems on Dentinal Cracks. *Journal of Endodontics*, 41(7): 1116–9.

De-Deus G, Moreira EJ, Lopes HP and Elias CN (2010) Extended Cyclic Fatigue Life of F2 Pro-Taper Instruments Used in Reciprocating Movement. *International Endodontic Journal*, 43: 1063–8.

De-Deus G, Silva EJNL, Vieira VTL, Belladonna FG, Elias CN, Plotino G and Grande NM (2017) Blue Thermomechanical Treatment Optimizes Fatigue Resistance and Flexibility of the Reciproc Files. *Journal of Endodontics*: 1–5.

De-Oliveira Alves V, Da Silveira Bueno CE, Cunha RS, Pinheiro SL, Fontana CE and De Martin AS (2012) Comparison among Manual Instruments and Pathfile and Mtwo Rotary Instruments to Create a Glide Path in the Root Canal Preparation of Curved Canals. *Journal of Endodontics*, 38(1): 117–20.

Debelian G and Trope M (2012), Scouting the Root Canal with Dedicated NiTi Files. *Roots*, 2: 24–7.

Dentsply Tulsa Dental Specialties (2015a) TRUShape 3D Confirming Files Brochure.

Dentsply Tulsa Dental Specialties (2015b) WaveOne Gold Brochure. available at https://www.dentsply.com/content/da%0Am/dentsply/pim/manufacturer/Endodontics/Obturation/Ob%0Aturators/Size_Verifiers/WaveOne_Gold_Size_Verifiers/W1GBrochure-%0AEN-jb8mf2z-en-1508.pdf.

Dhingra A, Kochar R, Banerjee S and Srivastava P (2014) Comparative Evaluation of the Canal Curvature Modifications after Instrumentation with One Shape Rotary and Wave One Reciprocating Files. *Journal of Conservative Dentistry*, 17: 138–41.

Dincer AN, Er O and Canakci BC (2015) Evaluation of Apically Extruded Debris during Root Canal Retreatment with Several NiTi Systems. *International Endodontic Journal*, 48: 1194–8.

Do-Amaral ROJF, Leonardi DP, Gabardo MCL, Coelho BS, de Oliveira KV and Filho FB (2016) Influence of Cervical and Apical Enlargement Associated with the Waveone System on the Transportation and Centralization of Endodontic Preparations. *Journal of Endodontics*: 1–6.

Dowker S, Davis G and Elliott J (1997) X-Ray Microtomography—nondestructive Three-Dimensional Imaging for in Vitro Endodontic Studies. *Oral Surgery Oral Medicine Oral Pathology Oral Radiology and Endodontology*, 83: 510–6.

Eleftheriadis G and Lambrianidis T (2005) Technical Quality of Root Canal Treatment and Detection of Iatrogenic Errors in an Undergraduate Dental Clinic. *International Endodontic Journal*, 38: 725–34.

Elnaghy AM and Elsaka SE (2014) Evaluation of Root Canal Transportation, Centering Ratio, and Remaining Dentin Thickness Associated with Protaper NEXT Instruments with and without Glide Path. *Journal of Endodontics*, 40(12): 2053–6.

Elnaghy AM and Elsaka SE (2015a) Evaluation of the Mechanical Behaviour of PathFile and ProGlider Pathfinding Nickel – Titanium Rotary Instruments. *International Endodontic Journal*: 894–901.

Elnaghy AM and Elsaka SE (2015b) Torsion and Bending Properties of OneShape and WaveOne Instruments. *Journal of Endodontics*, 41: 544–7.

Elnaghy AM and Elsaka SE (2016a) Mechanical Properties of ProTaper Gold Nickel-Titanium Rotary Instruments. *International Endodontic Journal*: 1073–8.

Elnaghy AM and Elsaka SE (2016b) Shaping Ability of ProTaper Gold and ProTaper Universal Files by Using Cone - Beam Computed Tomography. *Indian Journal of Dental Research*: 37–42.

Elnaghy AM and Elsaka SE (2016c) Effect of Sodium Hypochlorite and Saline on Cyclic Fatigue Resistance of WaveOne Gold and Reciproc Reciprocating Instruments. *International Endodontic Journal*: 1–8.

Elnaghy AM and Elsaka SE (2016d) Laboratory Comparison of the Mechanical Properties of TRUShape with Several Nickel-Titanium Rotary Instruments. *International Endodontic Journal*: 1–8.

Elsaka SE, Elnaghy AM and Badr AE (2016) Torsional and Bending Resistance of WaveOne Gold , Reciproc and Twisted File Adaptive Instruments. *International Endodontic Journal*, 50: 1–7.

Endal U, Shen Y, Knut A, Gao Y and Haapasalo M (2011) A High-Resolution Computed Tomographic Study of Changes in Root Canal Isthmus Area by Instrumentation and Root Filling. *Journal of Endodontics*, 37: 223–7.

Franco V, Fabiani C, Taschieri S, Malentacca A, Bortolin M and Del Fabbro M (2011) Investigation on the Shaping Ability of Nickel–titanium Files When Used with a Reciprocating Motion. *Journal of Endodontics*, 37: 1398–401.

Gagliardi J, Versiani M, De Sousa-Neto MD, Plazas-Garzon A and Basrani B (2015) Evaluation of the Shaping Characteristics of ProTaper Gold, ProTaper NEXT, and ProTaper Universal in Curved Canals. *Journal of Endodontics*, 41(10): 1718–24.

Gambarini G (2000) Rationale for the Use of Low-Torque Endodontic Motors in Root Canal Instrumentation. *Endodontics & Dental Traumatology*, 16: 95–100.

Gambarini G (2001) Cyclic Fatigue of ProFile Rotary Instruments after Prolonged Clinical Use. *International Endodontic Journal*, 34: 386–9.

Gambarini G, Giansiracusa Rubini A, Sannino G, Di Giorgio G, Piasecki L, Al-Sudani D, Plotino G and Testarelli L (2016) Cutting Efficiency of Nickel Titanium Rotary and Reciprocating Instruments after Prolonged Use. *Odontology*, 104: 77–81.

Gambarini G, Giansiracusa Rubini A, Al Sudani D, Gergi R, Culla A, De Angelis F, Di Carlo S, Pompa G, Osta N and Testarelli L (2012) Influence of Different Angles of Reciprocation on the Cyclic Fatigue of Nickel-Titanium Endodontic Instruments. *Journal of Endodontics*, 38: 1408–11.

Gambarini G, Plotino G, Sannino GP, Grande NM, Giansiracusa A, Piasecki L, da Silva Neto UX, Al-Sudani D and Testarelli L (2015) Cyclic Fatigue of Instruments for Endodontic Glide Path. *Odontology*, 103(1): 56–60.

Gambill JM, Alder M and Del Rio CE (1996) Comparison of Nickel-Titanium and Stainless Steel Hand-File Instrumentation Using Computed Tomography. *Journal of Endodontics*, 22(7): 369–375.

Garala M, Kuttler S, Hardigan P, Steiner-Carmi R and Dorn S (2003) A Comparison of the Minimum Canal Wall Thickness Remaining Following Preparation Using Two Nickel-Titanium Rotary Systems. *International Endodontic Journal*, 36: 636–42.

Generali L, Righi E, Todesca MV and Consolo U (2014) Canal Shaping with WaveOne Reciprocating Files: Influence of Operator Experience on Instrument Breakage and Canal Preparation Time. *Odontology*, 102: 217–22.

Gergi R, Rjeily JA, Sader J and Naaman A (2010) Comparison of Canal Transportation and Centering Ability of Twisted Files, Pathfile-ProTaper System, and Stainless Steel Hand K-Files by Using Computed Tomography. *Journal of Endodontics*, 36(5): 904–7.

Giansiracusa Rubini A, Plotino G, Al-Sudani D, Grande NM, Ermanno Putorti D, Sonnino GP, Cotti E, Testarelli T and Gambarini G (2014) A New Device to Test Cutting Efficiency of Mechanical Endodontic Instruments. *Medical Science Monitor*, 20: 374–8.

Glosson CR, Haller RH, Dove SB and Del Rio CE (1995) A Comparison of Root Canal Preparations Using NiTi Hand, NiTi Motor-Driven and K-Flex Endodontic Instruments. *Journal of Endodontics*, 21: 146–51.

Goldberg M, Dahan S and Machtou P (2012) Centering Ability and Influence of Experience When Using WaveOne Single-File Technique in Simulated Canals. *International Journal of Dentistry*: 1–7.

Grande NM, Mohamed H, Ahmed A and Cohen S (2015) Current Assessment of Reciprocation in Endodontic Preparation: A Comprehensive Review — Part I: Historic Perspectives and Current Applications. *Journal of Endodontics*, 41(11): 1778–83.

Grande NM, Plotino G and Ahmed HMA (2016) The Reciprocating Movement in Endodontics. *Endodontic Practice*: 28–33.

Greco K, Carmignani E and Cantatore G (2011) A Comparative Study between Manual and Mechanic Pre-Flaring Techniques, 14–7, in: *Paper presented to the Fifteenth Biennial Congress of the European Society of Endodontology*. Rome, Italy.

Greene KJ and Krell KV (1990) Clinical Factors Associated with Ledged Canals in Maxillary and Mandibular Molars. *Oral Surgery Oral Medicine and Oral Pathology*, 70: 490–7.

Griffiths IT, Bryant ST and Dummer PMH (2000) Canal Shapes Produced Sequentially during Instrumentation with Quantec LX Rotary Nickel-Titanium Instruments: A Study in Simulated Canals. *International Endodontic Journal*, 33: 346–54.

Griffiths IT, Chassot AL Nascimento MF, Bryant ST and Dummer PMH (2001) Canal Shapes Produced Sequentially during Instrumentation with Quantec SC Rotary Nickel-Titanium Instruments: A Study in Simulated Canals. *International Endodontic Journal*, 34: 107–12.

Ha JH, Lee CJ, Kwak SW, El Abed R, Ha D and Kim HC (2015) Geometric Optimization for Development of Glide Path Preparation Nickel-Titanium Rotary Instrument. *Journal of Endodontics*, 41(6): 916–9.

Haapasalo M, Endal U, Zandi H and Coil JM (2005) Eradication of Endodontic Infection by Instrumentation and Irrigation Solutions. *Endodontic Topics*, 10: 77–102.

Haikel Y, Serfaty R, Bateman G, Senger B and Allemann C (1999) Dynamic and Cyclic Fatigue of Engine-Driven Rotary Nickel-Titanium Endodontic Instruments. *Journal of Endodontics*, 25: 434–40.

Hashem AAR, Ghoneim AG, Lutfy RA, Foda MaY and Omar GAF (2012) Geometric Analysis of Root Canals Prepared by Four Rotary NiTi Shaping Systems. *Journal of Endodontics*, 38(7): 996–1000.

Health Professions Council of South Africa (2008), *General Ethical Guidelines for Health Researchers - Booklet 6*.

Hieawy A, Haapasalo M, Zhou H, Wang Z and Shen Y (2015) Phase Transformation Behavior and Resistance to Bending and Cyclic Fatigue of Protaper Gold and Protaper Universal Instruments. *Journal of Endodontics*, 41(7): 1134–8.

Hoffman JW and De Beer (2012) Characteristics of the Micro-Focus X-Ray Tomography Facility (MIXRAD) at Necsa in South Africa, in: *18th World Conference on Nondestructive Testing*. Durban, South Africa.

Hülsmann M, Herbst U and Schäfers F (2003) Comparative Study of Root-Canal Instruments Using Lightspeed and Quantec SC Rotary NiTi Instruments. *International Endodontic Journal*, 36: 748–56.

Hülsmann M, Peters OA and Dummer PMH (2005) Mechanical Preparation of Root Canals: Shaping Goals, Techniques and Means. *Endodontic Topics*, 10: 30–76.

Hwang YH, Bae KS, Baek SH, Kum KY, Lee WC, Shon WJ and Chang SW (2014) Shaping Ability of the Conventional Nickel-Titanium and Reciprocating Nickel-Titanium File Systems : A Comparative Study Using Micro – Computed Tomography. *Journal of Endodontics*, 40(8): 1186–9.

Iqbal MK, Kohli MR and Kim JS (2006) A Retrospective Clinical Study of Incidence of Root Canal Instrument Separation in an Endodontics Graduate Program: A PennEndo Database Study. *Journal of Endodontics*, 32: 1048–52.

Jafarzadeh H and Abbott PV (2007) Ledge Formation: Review of a Great Challenge in Endodontics. *Journal of Endodontics*, 33: 1155–62.

Jerome CE and Hanlon RJ Jr (2003) Identifying Multiplanar Root Canal Curvatures Using Stainless-Steel Instruments. *Journal of Endodontics*, 29: 356–8.

Johnson E, Lloyd A, Kuttler S and Namerow K (2008) Comparison between a Novel Nickel-Titanium Alloy and 508 Nitinol on the Cyclic Fatigue Life of Profile 25/.04 Rotary Instruments. *Journal of Endodontics*, 34(11): 1406–9.

Kapalas A and Lambrianidis T (2000) Factors Associated with Root Canal Ledging during Instrumentation. *Endodontics & Dental Traumatology.*, 16: 220–31.

Kaval ME and Capar ID (2017), Evaluation of the Cyclic Fatigue and Torsional Resistance of Novel Nickel-Titanium Rotary Files with Various Alloy Properties. *Journal of Endodontics*, 42(12): 10–13.

Kessler JR, Peters DD and Lorton L (1983) Comparison of the Relative Risk of Molar Root Perforations Using Various Endodontic Instrumentation Techniques. *Journal of Endodontics*, 9: 439–47.

Khatavkar RA and Hegde VS (2010) Importance of Patency in Endodontics. *Endodontology*, 22: 85–91.

Kim HC, Kwak SW, Cheung GSP, Ko DH, Chung SM and Lee W (2012) Cyclic Fatigue and Torsional Resistance of Two New Nickel Titanium Instruments Used in Reciprocation Motion: Reciproc versus WaveOne. *Journal of Endodontics*, 38: 541–4.

Kinsey B and Mounce RE (2008) Safe and Efficient Use of the M4 Safety Handpiece in Endodontics. *Roots*, 4: 36–40.

Kirchhoff AL, Chu R, Mello I, Garzon ADP, Dos Santos M and Cunha RS (2015) Glide Path Management with Single- and Multiple-Instrument Rotary Systems in Curved Canals: A Micro-Computed Tomographic Study. *Journal of Endodontics*, 41(11): 1880–3.

Kobayashi C, Yoshioka T and Suda H (1997) A New Engine-Driven Canal Preparation System with Electronic Canal Measuring Capability. *Journal of Endodontics*, 23: 751–4.

Lam TV, Lewis DJ, Atkins DR, Macfarlane RH, Clarkson RM, Whitehead MG, Brockhurst PJ and Moule AJ (1999) Changes in Root Canal Morphology in Simulated Curved Canals over-Instrumented with a Variety of Stainless Steel and Nickel Titanium Files. *Australian Dental Journal*, 44: 12–9.

Lambrianidis T (2009) Ledging and Blockage of Root Canals during Canal Preparation: Causes, Recognition, Prevention, Management, and Outcomes. *Endodontic Topics*, 15: 56–74.

Lindeburg MR (1999) *Civil Engineering Reference Manual for the PE Exam*. Belmont, CA: Professional Publications.

Loizides AL, Kakavetsos VD, Tzanetakis GN, Kontakiotis EG and Eliades G (2007) A Comparative Study of the Effects of Two Nickel-Titanium Preparation Techniques on Root Canal Geometry Assessed by Microcomputed Tomography. *Journal of Endodontics*, 33(12): 1455–9.

Lopes HP, Elias CN, Mangelli M, Lopes WSP, Amaral G, Souza LC and Siqueira JF Jr (2012) Buckling Resistance of Pathfinding Endodontic Instruments. *Journal of Endodontics*, 38(3): 402–4.

Lopes HP, Elias CN, Vieira VT, Moreira EJ, Marques RV, de Oliveira JC, Debelian G and Siqueira JF Jr (2010) Effects of Electropolishing Surface Treatment on the Cyclic Fatigue Resistance of BioRace Nickel-Titanium Rotary Instruments. *Journal of Endodontics*, 36: 1653–7.

Lopes HP, Gambarra-Soares T, Elias CN, Siqueira JF, Inojosa IFJ, Lopes WSP and Vieira VTL (2013) Comparison of the Mechanical Properties of Rotary Instruments Made of Conventional Nickel-Titanium Wire, M-Wire, or Nickel-Titanium Alloy in R-Phase. *Journal of Endodontics*, 39(4): 516–20.

Luisi SB, Zottis AC, Piffer CS, de Mello Vanzin AC and Ligabue RA (2010) Apical Extrusion of Debris after Hand, Engine Driven Reciprocating and Continuous Preparation. *Revista Odonto Ciência*, 25: 288–91.

Marzouk AM and Ghoneim AG (2013) Computed Tomographic Evaluation of Canal Shape Instrumented by Different Kinematics Rotary Nickel-Titanium Systems. *Journal of Endodontics*, 39: 906–9.

McKendry DJ (1990) Comparison of Balanced Forces, Endosonic and Step-Back Filing Instrumentation Techniques: Quantification of Extruded Apical Debris. *Journal of Endodontics*, 16: 24–7.

Miyai K, Ebihara A, Hayashi Y, Doi H, Suda H and Yoneyama T (2006) Influence of Phase Transformation on the Torsional and Bending Properties of Nickel-Titanium Rotary Endodontic Instruments. *International Endodontic Journal*, 39: 119–26.

Miyazaki S, Ohmi Y, Otsuka K and Suzuki Y((1982) Characteristics of Deformation and Transformation Pseudoelasticity in Ti-Ni Alloys. *Journal of Physique*, 43(12): 255–60.

Mol A (1999) Digital Quantitative Radiography: Tools and Toys. *Dentomaxillofacial Radiology*, 28: 328–9.

Moore.J, Fitz-Walter.P and Parashos.P (2009), A Micro-Computed Tomographic Evaluation of Apical Root Canal Preparation Using Three Instrumentation Techniques. *International Endodontic Journal*, 42(12): 1057–64.

Mounce RE (2005) Endodontic K-Files: Invaluable Endangered Species or Ready for the Smithsonian? *Dentistry Today*, 24: 102–4.

Mounce RE (2013) Using Hand Files to Their Full Capabilities : A New Look at an Old yet Emerging Technology. *Autralasian Dental Practie*, (June): 4–9.

Nahmias Y, Cassim I and Glassman G (2013), ‘ Own the Canal ’– the Importance of a Reproducible Glide Path. *Oral Health Journal*, (May): 74–82.

Nair MK and Nair UP (2007) Digital and Advanced Imaging in Endodontics: A Review. *Journal of Endodontics*, 33: 1–6.

Nakagawa RKL, Alves JL, Buono VTL and Bahia MGA (2014) Flexibility and Torsional Behaviour of Rotary Nickel-Titanium PathFile , RaCe ISO 10 , Scout RaCe and Stainless Steel K-File Hand Instruments. *International Endodontic Journal*, 47: 290–7.

Nielsen RB, Alyassinm AM, Peters DD, Carnes DL and Lancaster J (1995) Microcomputed Tomography: An Advanced System for Detailed Endodontic Research. *Journal of Endodontics*, 21: 561–8.

Oikonomou IA, Spanaki-Voreadi AP and Georgopoulou MK (2007) Procedural Errors during Root Canal Treatment Performed by Undergraduate Students in Athens: A Prospective Study. *International Endodontic Journal*, 40: 982.

Otsuka K and Ren X (2005) Physical Metallurgy of Ti-Ni-Based Shape Memory Alloys. *Progress in Materials Science*, 50: 511–678.

Ozyurek T (2016) Cyclic Fatigue Resistance of Reciproc, WaveOne, and WaveOne Gold Nickel-Titanium Instruments. *Journal of Endodontics*, 42(10): 1536–9.

Paleker F and Van der Vyver PJ (2016) Comparison of Canal Transportation and Centering Ability of K-Files, ProGlider File, and G-Files: A Micro-Computed Tomography Study of Curved Root Canals. *Journal of Endodontics*, 42(7): 1105–9.

Paleker F and Van Der Vyver PJ (2017) Glide Path Enlargement of Mandibular Molar Canals by Using K-Files, the Proglider File, and G-Files : A Comparative Study of the of the Preparation Times. *Journal of Endodontics*, 43(4): 609–12.

Paqué F, Ganahl D and Peters OA (2009) Effects of Root Canal Preparation on Apical Geometry Assessed by Micro-Computed Tomography. *Journal of Endodontics*, 35(7): 1056–9.

Parashos P and Messer HH (2006) Rotary NiTi Instrument Fracture and Its Consequences. *Journal of Endodontics*, 32: 1031–43.

Park SY, Cheung GS, Yum J, Hur B, Park JK and Kim HC (2010) Dynamic Torsional Resistance of Nickel-Titanium Rotary Instruments. *Journal of Endodontics*, 36: 1200–4.

Pasqualini D, Alovisi M, Cemenasco A, Mancini L, Paolino DS, Bianchi CC, Roggia A, Scotti N and Berutti E (2015) Micro-Computed Tomography Evaluation of ProTaper next and BioRace Shaping Outcomes in Maxillary First Molar Curved Canals. *Journal of Endodontics*, 41(10): 1706–10.

Pasqualini D, Bianchi CC, Paolino DS, Mancini L, Cemenasco A, Cantatore G, Castellucci A and Berutti E (2012) Computed Micro-Tomographic Evaluation of Glide Path with Nickel-Titanium Rotary PathFile in Maxillary First Molars Curved Canals. *Journal of Endodontics*, 38(3): 389–93.

Pedullà E, Grande NM, Plotino G, Gambarini G and Rapisarda E (2013) Influence of Continuous or Reciprocating Motion on Cyclic Fatigue Resistance of 4 Different Nickel-Titanium Rotary Instruments. *Journal of Endodontics*, 39: 258–61.

Pedullà E, Lo Savio F, Boninelli S, Plotino G, Grande NM, Rapisarda E and La Rosa G (2015) Influence of Cyclic Torsional Preloading on Cyclic Fatigue Resistance of Nickel-Titanium Instruments. *International Endodontic Journal*, 48: 1043–50.

Pereira ES, Singh R, Arias A and Peters OA (2013) In Vitro Assessment of Torque and Force Generated by Novel ProTaper Next Instruments during Simulated Canal Preparation. *Journal of Endodontics*, 39: 1615–9.

Pereira ESJ, Gomes RO, Leroy AMF, Singh R, Peters OA, Bahia MGA and Buono VTL (2103) Mechanical Behavior of M-Wire and Conventional NiTi Wire Used to Manufacture Rotary Endodontic Instruments. *Dental Materials*, 29(12): 318–24.

Pereira ESJ, Peixoto IFC, Viana ACD, Oliveira II, Gonzalez BM, Buono VTL and Bahia MGA (2011) Physical and Mechanical Properties of a Thermomechanically Treated NiTi Wire Used in the Manufacture of Rotary Endodontic Instruments. *International Endodontic Journal*, 45(5): 469–74.

Pérez-Higueras JJ, Arias A and De la Macorra JC (2013) Cyclic Fatigue Resistance of K3, K3XF, and Twisted File Nickel-Titanium Files under Continuous Rotation or Reciprocating Motion. *Journal of Endodontics*, 39: 1585–8.

Peters OA (2004) Current Challenges and Concepts in the Preparation of Root Canal Systems: A Review. *Journal of Endodontics*, 30: 559–67.

Peters OA, Laib A, Go TN and Barbakow F (2001) Changes in Root Canal Geometry after Preparation Assessed by High-Resolution Computed Tomography. *Journal of Endodontics*: 1–6.

Peters OA and Paqué F (2010) Current Developments in Rotary Root Canal Instrument Technology and Clinical Use: A Review. *Quintessence International*, 41: 479–88.

Peters OA and Paqué F (2011) Root Canal Preparation of Maxillary Molars with the Self-Adjusting File: A Micro-Computed Tomography Study. *Journal of Endodontics*, 37(1): 53–7.

Peters OA, Peters CI and Scho K (2003) ProTaper Rotary Root Canal Preparation: Assessment of Torque and Force in Relation to Canal Anatomy. *International Endodontic Journal*: 93–9.

Peters OA, Peters CI, Schönenberger K and Barbakow F (2003) ProTaper Rotary Root Canal Preparation: Effects of Canal Anatomy on Final Shape Analysed by Micro CT. *International Endodontic Journal*, 36(2): 86–92.

Pettiette MT, Metzger Z, Phillips C and Trope M (1999) Endodontic Complications of Root Canal Therapy Performed by Dental Students with Stainless-Steel and Nickel-Titanium Hand Files. *Journal of Endodontics*, 25(4): 230–4.

Plotino G, Giansiracusa Rubini A, Grande NM, Testarelli L and Gambarini G (2014) Cutting Efficiency of Reciproc and WaveOne Reciprocating Instruments. *Journal of Endodontics*, 40: 1228–30.

Plotino G, Grande NM, Cordaro M, Testarelli L and Gambarini G (2009) A Review of Cyclic Fatigue Testing of Nickel-Titanium Rotary Instruments. *Journal of Endodontics*, 35: 1469–76.

Plotino G, Grande NM, Mercad M, Testarelli L and Gambarini G (2017) Influence of Temperature on Cyclic Fatigue Resistance of ProTaper Gold and ProTaper Universal Rotary Files. *Journal of Endodontics*: 2016–8.

Plotino G, Grande NM and Porciani PF (2015) Deformation and Fracture Incidence of Reciproc Instruments: A Clinical Evaluation. *International Endodontic Journal*, 48: 199–205.

Plotino G, Grande NM, Testarelli L and Gambarini G (2012) Cyclic Fatigue of Reciproc and Wave- One Reciprocating Instruments. *International Endodontic Journal*, 45: 614–8.

Plotino G, Mohamed H, Ahmed A, Grande NM and Cohen S (2015) Current Assessment of Reciprocation in Endodontic Preparation: A Comprehensive Review — Part II: Properties and Effectiveness. *Journal of Endodontics*, 41(12): 1939–50.

Powell SE, Simon JH and Maze BB (1986) A Comparison of the Effect of Modified and Nonmodified Instrument Tips on Apical Canal Configuration. *Journal of Endodontics*, 12: 293–300.

Pruett JP, Clement DJ and Carnes DL Jr (1997) Cyclic Fatigue Testing of Nickeltitanium Endodontic Instruments. *Journal of Endodontics*, 23: 77–85.

Reddy SA and Hicks ML (1994) Apical Extrusion of Debris Using Two Hand and Two Rotary Instrumentation Techniques. *Journal of Endodontics*, 24: 180–3.

Rhodes JS, Pitt Ford TR and Lynch JA (2000) A Comparison of Two Nickel-Titanium Instrumentation Techniques in Teeth Using Microcomputed Tomography. *International Endodontic Journal*, 33: 279–85.

Robinson JP, Lumley PJ, Cooper PR, Grover LM and Walmsley AD (2013) Reciprocating Root Canal Technique Induces Greater Debris Accumulation than a Continuous Rotary Technique as Assessed by 3-Dimensional Micro-Computed Tomography. *Journal of Endodontics*, 39: 1067–70.

Roland DD, Andelin WE, Browning DF, Hsu GHR and Torabinejad M (2002) The Effect of Preflaring on the Rates of Separation for 0.04 Taper Nickel Titanium Rotary Instruments. *Journal of Endodontics*, 28(7): 543–5.

Ruddle CJ (2002) Cleaning and Shaping the Root Canal System, , in: Cohen, S. and Burns, R. (Eds.), *Pathways of the Pulp*. St Louis, Missouri: Mosby.

Ruddle CJ (2005) The ProTaper Technique. *Endodontic Topics*, 19: 187–90.

Ruddle CJ (2012) Endodontic Canal Preparation: WaveOne Single-File Technique. *Dentistry Today*: 124–9.

Ruddle CJ (2014) Advanced Endodontics: Proglider. available at http://www.endoruddle.com/proglider

Ruddle CJ (2016) Single-File Shaping Technique: Achieving a Gold Medal Result. *Dentistry Today*, (January): 1–7.

Saber SE, Nagy MM and Schäfer E (2015) Comparative Evaluation of the Shaping Ability of WaveOne, Reciproc and OneShape Single-File Systems in Severely Curved Root Canals of Extracted Teeth. *International Endodontic Journal*, 48: 109–14.

Saber Sel D and Abu El Sadat SM (2013) Effect of Altering the Reciprocation Range on the Fatigue Life and the Shaping Ability of WaveOne Nickel-Titanium Instruments. *Journal of Endodontics*, 39: 685–8.

Saberi N, Patel S and Mannocci F (2017) Comparison of Centring Ability and Transportation between Four Nickel Titanium Instrumentation Techniques by Micro-Computed Tomography. *International Endodontic Journal*, 50(6): 595–603.

Saleh AM, Tavanafar S, Vakili-Gilani P, Al Sammerraie NJ and Rashid F (2013) Influence of Operator's Experience Level on Lifespan of the WaveOne Primary File in Extracted Teeth. *Restorative Dentistry & Endodontics*, 38(4): 222–6.

Saleh AM, Vakili Gilani P, Tavanafar S and Schäfer E (2015) Shaping Ability of 4 Different Single-File Systems in Simulated S-Shaped Canals. *Journal of Endodontics*, 41: 548–52.

Sanches Cunha R, Junaid A, Ensinas P, Nudera W and Da Silveira Bueno ED (2014) Assessment of the Separation Incidence of Reciprocating WaveOne Files: A Prospective Clinical Study. *Journal of Endodontics*, 40: 922–4.

Sathorn C, Palamara JEA and Messer HH (2005) A Comparison of the Effects of Two Canal Preparation Techniques on Root Fracture Susceptibility and Fracture Pattern. *Journal of Endodontics*, 31: 283–7.

Sattapan B, Nervo GJ, Palamara JEA and Messer HH (2000) Defects in Rotary Nickel-Titanium Files after Clinical Use. *Journal of Endodontics*, 26: 161–5.

Sattapan B, Palamara JE and Messer HH (2000) Torque during Canal Instrumentation Using Rotary Nickel-Titanium Files. *Journal of Endodontics*, 26: 156–60.

Schäfer E and Dammaschke T (2009) Development and Sequelae of Canal Transportation. *Endodontic Topics*, (4): 75–90.

Schäfer E, Tepel J and Hoppe W (1995) Properties of Endodontic Hand Instruments Used in Rotary Motion. Part 2: Instrumentation of Curved Canals. *Journal of Endodontics*, 21: 493–7.

Schilder H (1974) Cleaning and Shaping the Root Canal. *Dental Clinics of North America*, 18: 269–296.

Schneider SW (1971) A Comparison of Canal Preparations in Straight and Curved Root Canals. *Oral Surgery Oral Medicine Oral Pathology Oral Radiology and Endodontology*, 32: 271–5.

Schrader C, Ackermann M and Barbakow F (1999) Step-by-Step Description of a Rotary Root Canal Preparation Technique. *International Endodontic Journal*, 32: 312–20.

Scianamblo MJ (2011), USPTO 6942484, 7094056,7955078 and 20060228669.Attorney: Fish & Richardson P.C Current U.S Classification: 433/102, International Classification A61C005/02, 2011.

Setzer FC, Kwon TK and Karabucak B (2010) Comparison of Apical Transportation between Two Rotary File Systems and Two Hybrid Rotary Instrumentation Sequences. *Journal of Endodontics*, 36: 1226–9.

Shen Y, Qian W, Abtin H, Gao Y and Haapasalo M (2011), Fatigue Testing of Controlled Memory Wire Nickel-Titanium Rotary Instruments. *Journal of Endodontics*, 37: 997–1001.

Shen Y, Zhou HM, Zheng YF, Campbell L, Peng B and Haapasalo M (2011), Metallurgical Characterization of Controlled Memory Wire Nickel-Titanium Rotary Instruments. *Journal of Endodontics*, 37: 1566–71.

Shin CS, Huang YH, Chi CW and Lin CP (2014) Fatigue Life Enhancement of NiTi Rotary Endodontic Instruments by Progressive Reciprocating Operation. *International Endodontic Journal*, 47: 882–8.

Short JA, Morgan LA and Baumgartner JC (1997) A Comparison of Canal Centering Ability of Four Instrumentation Techniques. *Journal of Endodontics*, 23: 503–7.

Shuping GB, Ørstavik D, Sigurdsson A and Trope M (2000) Reduction of Intracanal Bacteria Using Nickel- Titanium Rotary Instrumentation and Various Medications. *Journal of Endodontics*, 26: 751–5.

Silva EJ, Sá L, Belladonna FG, Neves AA, Accorsi-Mendonça T, Vieira VT, De-Deus G and Moreira EJ (2014) Reciprocating versus Rotary Systems for Root Filling Removal: Assessment of the Apically Extruded Material. *Journal of Endodontics*, 40: 2077–80.

Silva EJNL, Muniz BL, Pires F, Neves A, Souza EM and De-deus G (2016) Comparison of Canal Transportation in Simulated Curved Canals Prepared with ProTaper Universal and ProTaper Gold Systems. *Restorative Dentistry & Endodontics*, 41: 1–5.

Siqueira JF Jr (2003) Microbial Causes of Endodontic Flare-Ups. *International Endodontic Journal*, 36: 453–63.

Siqueira JF Jr, Rôças IN, Favieri A, Machado AG, Gahyva SM, Oliveira JC and Abad EC (2002) Incidence of Postoperative Pain after Intracanal Procedures Based on an Antimicrobial Strategy. *Journal of Endodontics*, 28: 457–60.

Sjøgren U, Figdor D, Persson S and Sundqvist G (1997) Influence of Infection at the Time of Root Filling on the Outcome of Endodontic Treatment of Teeth with Apical Periodontitis. *International Endodontic Journal*, 30: 297–306.

Tambe VH, Nagmode PS, Abraham S, Patait M, Lahoti PL and Jaju N (2014) Comparison of Canal Transportation and Centering Ability of Rotary Protaper, One Shape System and Wave One System Using Cone Beam Computed Tomography: An in Vitro Study. *Journal of Conservative Dentistry*, 17: 561–5.

Tasdemir T, Aydemir H, Inan U and Ünal O (2005) Canal Preparation with Hero 642 Rotary Ni-Ti Instruments Compared with Stainless Steel Hand K-File Assessed Using Computed Tomography. *International Endodontic Journal*, 38: 402–8.

Thompson SA (2000) An Overview of Nickel-Titanium Alloys Used in Dentistry. *International Endodontic Journal*, 33: 297– 310.

Thompson SA and Dummer PMH (1997) Shaping Ability of ProFile 04 Taper Series 29 Rotary Nickel-Titanium Instruments in Simulated Root Canals. *International Endodontic Journal*, 30: 1–7.

Tocci L, Plotino G, Al-Sudani D, Giansiracusa Rubini A, Sannino G, Piasecki L, Putortì E, Testarelli L and Gambarini G (2015) Cutting Efficiency of Instruments with Different Movements: A Comparative Study. *Journal of Oral and Maxillofacial Research*, 6(1): 6.

Topcuoglu HS, Duzgun S, Akti A and Topcuoglu G (2016) Laboratory Comparison of Cyclic Fatigue Resistance of WaveOne Gold , Reciproc and WaveOne Files in Canals with a Double Curvature. *International Endodontic Journal*: 1–5.

Türker SA, Saglam BC, Kocak MM and Kocak S (2014) The Effect of Glide Path on the Surface Quality of New and Used Rotary and Reciprocating Single Files: OneShape versus WaveOne. *Scanning*, 36: 608–13.

Türker SE, Uzunoğlu E and Aslan MH (2015) Evaluation of Apically Extruded Bacteria Associated with Different Nickel-Titanium Systems. *Journal of Endodontics*, 41: 953–5.

Urbaniak GC and Plous S (2016) Research Randomizer. *Social Psychology Network*. available at https://www.randomizer.org/

Uygun AD, Kol E, Topcu MKC, Seckin F, Ersoy I and Tanriver M (2016) Variations in Cyclic Fatigue Resistance among ProTaper Gold , ProTaper Next and ProTaper Universal Instruments at Different Levels. *International Endodontic Journal*, 49: 494–9.

Vadhana S, SaravanaKarthikeyan B, Nandini S and Velmurugan N (2014) Cyclic Fatigue Resistance of RaCe and Mtwo Rotary Files in Continuous Rotation and Reciprocating Motion. *Journal of Endodontics*, 40: 995–9.

Varela-Patiño P, Ibañez-Párraga A, Rivas-Mundiña B, Cantatore G, Otero XL and Martin-Biedma B (2010) Alternating versus Continuous Rotation: A Comparative Study of the Effect on Instrument Life. *Journal of Endodontics*, 36(1): 157–9.

Varela-Patiño P, Martin-Biedma B, Liébana CR, Cantatore G and Bahillo JG (2005) The Influence of a Manual Glide Path on the Separation Rate of NiTi Rotary Instruments. *Journal of Endodontics*, 31(2): 114–6.

Varela-Patiño P, Martín-Biedma B, Rodriguez-Nogueira J, Cantatore G, Malentaca A and Ruiz-Pinón M (2008) Fracture Rate of Nickel-Titanium Instruments Using Continuous versus Alternating Rotation. *Endodontic Practice*, 3: 193–7.

Versluis A, Messer HH and Pintado MR (2006) Changes in Compaction Stress Distributions in Roots Resulting from Canal Preparation. *International Endodontic Journal*, 9: 931–9.

Versümer J, Hülsmann M and Schäfers F (2002), A Comparative Study of Root Canal Preparation Using ProFile .04 and Lightspeed Rotary Ni-Ti Instruments. *International Endodontic Journal*, 35: 37–46.

Volume Graphics GMBH (2014), 3D Volume Rendering Software: VGStudio MAX. available at http://www.volumegraphics.com/en/products/vgstudio-max/ct-reconstruction/

Van der Vyver PJ (2011) Creating a Glide Path for Rotary NiTi Instruments: Part One. *Endodontic Practice*, February: 40–3.

Van der Vyver PJ (2014) Proglider: Clinical Protocol. *Endodontic Practice*, (May): 12–17.

Van der Vyver PJ, Paleker F and Jonker CH (2015) Comparison of Preparation Times of Three Different Rotary Glide Path Instrument Systems. *South African Dental Journal*, 70(4): 146–9.

Van der Vyver PJ and Scianamblo MJ (2013) Clinical Guidelines for the Use of ProTaper Next Instruments (Part I). *Endodontic Practice*, (December):33-40.

Wagner MH, Barletta FB, Reis Mde S, Mello LL, Ferreira R and Fernandes AL (2006) NSK Reciprocating Handpiece: In Vitro Comparative Analysis of Dentin Removal during Root Canal Preparation by Different Operators. *Brazilian Dental Journal*, 17(1): 10–4.

Walia HM, Brantley WA and Gerstein H (1988) An Initial Investigation of the Bending and Torsional Properties of Nitinol Root Canal Files. *Journal of Endodontics*, 14: 346–51.

Walsch H (2004) The Hybrid Concept of Nickel-Titanium Rotary Instrumentation. *Dental Clinics of North America*, 48: 183–202.

Walton RE and Torabinejad M (2002) *Principles and Practice of Endodontics*. Philadelphia: WB Saunders.

Wan J, Rasimick BJ, Musikant BL and Deutsch AS (2011) A Comparison of Cyclic Fatigue Resistance in Reciprocating and Rotary Nickel-Titanium Instruments. *Australian Endodontic Journal*, 31: 122–7.

Webber J (2015) Shaping Canals with Confidence : WaveOne GOLD Single-File. *Roots*, 1: 34–40.

Webber J, Machtou P, Pertot W, Kuttler S and West J (2011) The WaveOne™ Single-File Reciprocating System. *Roots*, (1): 1–9.

Weine F (1996) *Endodontic Therapy*. St Louis: Mosby.

West J (2006) Endodontic Update 2006. *Journal of Esthetic and Restorative Dentistry*, 18: 280–300.

West JD (2010) The Endodontic Glidepath: 'secret to Rotary Safety'. *Dentistry Today*, 29(9): 86–3.

Wu MK, Fan B and Wesselink PR (2000) Leakage along Apical Root Fillings in Curved Root Canals. Part I: Effects of Apical Transportation on Seal of Root Fillings. *Journal of Endodontics*, 26: 210–16.

Wycoff RC and Berzins DW (2012) An in Vitro Comparison of Torsional Stress Properties of Three Different Rotary Nickeltitanium Files with a Similar Cross-Sectional Design. *Journal of Endodontics*, 38: 1118–20.

Xu X, Eng M, Zheng Y and Eng D (2006) Comparative Study of Torsional and Bending Properties for Six Models of Nickeltitanium Root Canal Instruments with Different Cross-Sections. *Journal of Endodontics*, 32: 372–5.

Yamamura B, Cox T, Heddaya B, Flake NM, Johnson JD and Paranjpe A (2012) Comparing Canal Transportation and Centering Ability of Endosequence and Vortex Rotary Files by Using Micro-Computed Tomography. *Journal of Endodontics*, 38(8): 1121–5.

Yared GM, Bou Dagher FE and Machtou P (1999) Cyclic Fatigue of ProFile Rotary Instruments after Simulated Clinical Use. *International Endodontic Journal*, 32: 115–9.

Yared GM, Bou Dagher FE and Machtou P (2001) Influence of Rotational Speed, Torque and Operator's Proficiency on ProFile Failure. *International Endodontic Journal*, 34: 47–53.

Ye J and Gao Y (2012) Metallurgical Characterization of M-Wire Nickel-Titanium Shape Memory Alloy Used for Endodontic Rotary Instruments during Low-Cycle Fatigue. *Journal of Endodontics*, 38: 105–7.

Yoneyama T and Kobayashi C (2009) Endodontic Instruments for Root Canal Treatment Using Ni-Ti Shape Memory Alloys, 297–305, in: Oneyama T, and Miyazaki S. (Eds.), *Shape Memory Alloys for Biomedical Applications*. Cambridge, England: Woodhead Publishing Limited.

You SY, Bae KS, Baek SH, Kum KY, Shon WJ and Lee W (2010) Lifespan of One Nickel-Titanium Rotary File with Reciprocating Motion in Curved Root Canals. *Journal of Endodontics*, 36: 1991–4.

You YS and Cho YB (2012) A Comparison of the Shaping Ability of Reciprocating NiTi Instruments in Simulated Curved Canals. *Restorative Dentistry and Endodontics*, 37: 220–7.

Young GR, Parashos P and Messer HH (2007) The Principles of Techniques for Cleaning Root Canals. *Australian Dental Journal*, 52(Supplement 1): 52–63.

Chapter 8: Addenda

Appendix A: Participant's Information & Informed Consent

RESEARCH TITLE: A Micro-Computed Tomographic Evaluation of Curved Maxillary Molar Root Canals After Using Different Root Canal Instrumentation Techniques

SPONSOR: Researcher – Prof PJ van der Vyver

Principal Investigators: Prof PJ van der Vyver

Institution: Pretoria Oral and Dental Hospital, University of Pretoria

DAY TIME AND AFTER HOURS TELEPHONE NUMBER(S):

Day time numbers: 011 781 1020

After hours: 0824104293

DATE AND TIME OF FIRST INFORMED CONSENT DISCUSSION:

dd	**mm**	**yy**

:
Time

Dear Patient

INTRODUCTION

You are **invited** to volunteer for a research study. This information leaflet is to help you to decide if you would like to participate. Before you agree to take part in this study you should fully understand what is involved. If you have any questions, which are not fully explained in this leaflet, do not hesitate to ask the investigator. You should not agree to take part unless you are completely happy about all the procedures involved. In the best interests of your health, it is strongly recommended that you discuss with or inform your personal doctor of your possible participation in this study, wherever possible.

WHAT IS THE PURPOSE OF THE RESEARCH?

The purpose of the research is to evaluate which root canal file system prepares teeth in the most favorable way when doing root canal treatment. Once your tooth that is deemed not restorable is extracted it will be prepared with different file systems and evaluated for its preparation properties.

WHAT IS THE DURATION OF THIS RESEARCH?

If you decide to take part you will be one of approximately sixty patients. No follow up visits will be necessary.

DESCRIPTION OF PROCEDURES

This study involves three-dimensional scanning of extracted teeth after being prepared with different root canal preparation files. Teeth will be randomized and divided into three different preparation groups. After preparation, teeth will be scanned and evaluated to see which system prepared the teeth in the most favourable way.

HAS THE RESEARCH RECEIVED ETHICAL APPROVAL?

This clinical trial Protocol was submitted to the Faculty of Health Sciences Research Ethics Committee, University of Pretoria, telephone numbers 012 356 3084 / 012 356 3085 and written approval has been granted by that committee. The study has been structured in accordance with the Declaration of Helsinki (last update: October 2008), which deals with the recommendations guiding doctors in biomedical research involving human/subjects. A copy of the Declaration may be obtained from the investigator should you wish to review it.

WHAT ARE YOUR RIGHTS AS A PARTICIPANT IN THIS RESEARCH?

Your participation in this research is entirely voluntary and you can refuse to participate. Your refusal will not affect your access to other medical care.

MAY ANY OF THESE RESEARCH PROCEDURES RESULT IN DISCOMFORT OR INCONVENIENCE?

There are no risks involved in participating in this study. Teeth will be used for research purposes only after extraction. It is important to note that no teeth will be extracted solely for this study and that teeth extracted would have been extracted regardless of the study.

WHAT ARE THE BENEFITS TO YOU?

Although you will not benefit directly from this study, the results of the study will enable us to improve pulp treatment in permanent teeth.

WHAT ARE THE RISKS INVOLVED IN THIS RESEARCH?

Your participation in this study is entirely voluntary. You can refuse to participate by not giving permission to use extracted teeth for this research project.
There are no risks involved in participating in this study.

ARE THERE ANY WARNINGS OR RESTRICTIONS CONCERNING MY PARTICIPATION IN THIS TRIAL?

No. The contact person for this investigation is Prof PJ van der Vyver (012 319 2231). You are welcome to contact him should you require any additional information.

CONFIDENTIALITY

All information obtained during the course of this trial is strictly confidential. Data that may be reported in scientific journals will not include any information, which identifies you as a patient in this research.

COMPENSATION

Participation is voluntary. No compensation or contribution will be given for your participation

INFORMED CONSENT

I hereby confirm that I have been informed by the investigator, Prof Peet van der Vyver about the nature, conduct, benefits, and risks of above-mentioned research. I have also received, read, and understood the above written information (Patient Information Leaflet and Informed Consent) regarding the research.

I am aware that the results of the research, including personal details regarding my sex, age, date of birth, initials and diagnosis will be anonymously processed into a research report.

I may, at any stage, without prejudice, withdraw my consent and participation in the research. I have had sufficient opportunity to ask questions and (of my own free will) declare myself prepared to participate in the research.

Patient's Name: ____

(Please print)

Patient's Signature: __________________ Date: _____________

I, Prof PJ van der Vyver herewith confirm that the above patient has been informed fully about the nature, conduct, and risks of the above research.

Investigator's Name: ____

(Please print)

Investigator's Signature: _________________ Date: _____________

Witness's Name: ____

Witness's Signature: _____________________ Date: _____________

(Please print)

VERBAL PATIENT INFORMED CONSENT (applicable when patients cannot read or write)

I, the undersigned, Prof PJ van der Vyver, have read and have explained fully to the patient, named ……………….. and/or, his/her relative, the patient information leaflet, which has indicated the nature and purpose of the research in which I have asked the patient to participate. The explanation I have given has mentioned both the possible risks and benefits of the research and the alternative treatments available for his/her illness. The patient indicated that he/she understands that he/she will be free to withdraw from the research at any time for any reason and without jeopardizing his/her subsequent injury attributable to the drug(s) used in the clinical trial, to which he/she agrees.

I hereby certify that the patient has agreed to participate in this research.

Patient's Name: ____

(Please print)

Investigator's Name: ____

(Please print)

Investigator's Signature:__________________ Date: _____________

Witness's Name: ____

Witness's Signature__________________ Date: _____________

Appendix B: Ethics Protocol Approval

The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.
- FWA 00002567, Approved dd 22 May 2002 and Expires 20 Oct 2016.
- IRB 0000 2235 IORG0001762 Approved dd 22/04/2014 and Expires 22/04/2017.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences Research Ethics Committee

18/08/2016

Approval Certificate
New Application

Ethics Reference No.: 296/2016

Title: A Micro-Computed Tomographic Evaluation of Curved Maxillary Molar Root Canals Using Different Root Canal Instrumentation Techniques

Dear Prof Petrus van der Vyver

The **New Application** as supported by documents specified in your cover letter dated 12/08/2016 for your research received on the 12/08/2016, was approved by the Faculty of Health Sciences Research Ethics Committee on its quorate meeting of 17/08/2016.

Please note the following about your ethics approval:
- Ethics Approval is valid for 2 years
- Please remember to use your protocol number (**296/2016**) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, or monitor the conduct of your research.

Ethics approval is subject to the following:
- The ethics approval is conditional on the receipt of **6 monthly written Progress Reports**, and
- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

Additional Conditions:
- The REC waives the need for individual consent.

We wish you the best with your research.

Yours sincerely

Dr R Sommers; MBChB; MMed (Int); MPharMed,PhD
Deputy Chairperson of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes 2004 (Department of Health).

☎ 012 356 3084 deepeka.behari@up.ac.za / fhsethics@up.ac.za http://www.up.ac.za/healthethics
✉ Private Bag X323, Arcadia, 0007 - Tswelopele Building, Level 4, Room 60, Gezina, Pretoria