Comparisons of the Shaping Abilities of Three NiTi File Systems Using Rotational versus Reciprocal Movements

A THESIS SUBMITTED TO THE FACULTY
OF THE UNIVERSITY OF MINNESOTA
BY

Tyler Blaine Peterson, DDS

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Dr. Scott McClanahan

August 2014

Dedication

To my Parents, Douglas and Louise, for their lifetime of love and unyielding support

To Mercedes for giving me the strength and support to follow my dreams, even when I did not think they were possible

Acknowledgements

I would like to express my sincere gratitude to the following people:

Dr. Scott McClanahan, Dr. Walter Bowles

For your assistance and guidance in helping me complete this study, and for serving on my examining committee.

Michael Reagan Anderson, Jason Yick

Thank you for your many hours of work, and dedication to this research endeavor.

Dr. Scott Brezinsky

For your counsel and advise on how best to tackle problems encountered.

The MDRCBB

For your guidance, help and trust. Thank you to all of the people on the 16th floor who spent time answering my questions and training me.

Scott Lunos

For your support and skill in statistical analysis.

Abstract

Introduction: The purpose of this study was to determine if there were any differences in shaping abilities between three NiTi file systems when using rotational versus reciprocal movements in simulated S-shaped canals, as well as compare the time required to complete canal preparations.

Methods: One hundred twenty S-shaped canals were filled with ink and pre-instrumentation images were obtained using a stereomicroscope. Experimental canal preparations where completed using K3XF in rotary movement, K3XF in reciprocal movement, Twisted File (TF) in rotary movement, TF in reciprocal movement, ProTaper Next (PTN) in rotary movement, and PTN in reciprocal movement. Pre-instrumentation and post-instrumentation images were superimposed, and standardized for area difference measurements. Pre-instrumentation and post-instrumentation area differences were measured in seven defined regions and the mean differences were compared between the experimental instrumentation groups. Time required to complete canal preparations was recorded for each group for comparisons.

Results: Statistical analysis showed there were significant differences between NiTi file systems, instrumentation movement type, as well as time to complete canal preparations. The TF file system performed better in shaping abilities than the PTN file system followed by the K3XF file system in a majority of the defined areas measured. The TF file system performed the best in reciprocal motion in all defined regions compared to the TF in rotary motion. Reciprocal motion was better in shaping ability compared to rotary motion in a majority of the defined areas measured. The K3XF file system in reciprocal motion completed canal preparations quicker than the K3XF file system in rotary motion.

Conclusions: Differences were found between K3XF, TF, and PTN file systems in regards to shaping abilities, rotatory versus reciprocal motions, and canal preparation times.

TABLE OF CONTENTS

List of Figures

List of Tables

Introduction

The hallmark of successful root canal therapy is the removal of intracanal microorganisms, which are responsible for endodontic pathosis. This is accomplished through the implementation of specific instruments and irrigants that are used to debride, shape, and disinfect the root canal space within a tooth. Ideal instrumentation principles were described by Dr. Herbert Schilder who advocated that the preparation should result in a continuously tapering funnel from the coronal access to the root apex, maintain the original canal anatomy, keep the apical foramen in its original position with respect to the periapical tissues and the root surface, as well as keep the apical foramen as small as reasonably possible (1).

Historically, stainless steel (SS) hand file instruments have been used in order to accomplish the preparation goals described by Schilder. However, one of the main disadvantages of stainless steel files is that as the size of the file increases, the stiffness of the file also increases (2). In curved canals, this can lead to procedural errors such as canal transportation, apical zipping, canal ledges, and strip perforations (3, 4). Canal transportation is an undesirable error that can occur during instrumentation and results in a canal preparation that is deviated from the original canal anatomy (5). This can be particularly detrimental in molar teeth if the transportation of the canal results in a canal that is shifted toward the furcation. Canal transportation toward the furcation may result in a perforation of the root, which may compromise the prognosis of the tooth. Studies have shown that the thickness of root dentin in furcation areas of mandibular molar roots can be as minimal as 1.2 mm (6).

The more elastic nature of modern nickel titanium (NiTi) instruments has helped to reduce procedural errors during canal shaping. NiTi rotary files have become the standard of care for preparation of the root canal system in endodontics because of their greater flexibility (7), their ability to stay more centered in the canal (8), and because they cause less canal transportation (9) when compared to stainless steel hand files. Rotary NiTi files are not without their own set of disadvantages however, and one of the biggest concerns when using NiTi files is fracture of the instrument during treatment. Fracture of rotary NiTi instruments occurs by one of two mechanisms: facture by torsional or flexural fatigue (10). Torsional fracture occurs when part of the instrument becomes locked in the canal while the shank of the instrument continues to rotate. If the elastic limit of the NiTi file is exceeded when the instrument is locked in the canal then the instrument will fracture (10). This has negative effects on the canal preparation goals because often times the fractured file cannot be removed from the canal, and may limit the ability to effectively clean, shape, and obturate the tooth.

Recently, a new approach in endodontic instrumentation has been developed, which utilizes a reciprocating movement versus rotating movement of NiTi files, which helps to overcome torsional fracture complications (11). The reciprocating movement aims to reduce the risk of instrument fracture by engaging the file in a cutting motion, and then immediately disengaging it in a non-cutting motion. The cutting/engaging motion is designed to be below the elastic limit of the file, so that torsional fatigue is minimized or avoided all together. Since the elastic limit of the file is theoretically never met, this will ultimately lead to less or no instrument fracture. The NiTi reciprocating concept is based on the balanced force hand filing technique developed originally by Dr. Roane in 1985, which was shown to be effective at negotiating curved canals with large hand files while maintaining the original canal shape (12).

Reciprocating NiTi file systems represent a new paradigm in root canal instrumentation with the possibility of reducing procedural errors and complications. The purpose of this study is to evaluate how three NiTi file systems perform in regard to their canal shaping ability in simulated S-shaped canals when using rotational movement versus reciprocal movement.

Review of the Literature

Objectives of Root Canal Instrumentation

Treatment of pulpal and apical pathoses is the primary goal of endodontic therapy, which ultimately leads to the elimination of infection and allows for retention of the natural tooth. Infiltration and subsequent infection of the root canal system by microorganisms and their byproducts is the primary etiology of endodontic pathosis (13). The goal of root canal therapy is to remove these microorganisms and their byproducts, as well as any remaining vital or necrotic pulpal remnants, through the use of specialized instruments and irrigants that are used to debride, shape and disinfect the root canal space. In 1974, Herbert Schilder published *Cleaning and Shaping the Root Canal*, in which he introduced concepts that remain the foundation of successful endodontic therapy to this day. Dr. Schilder was adamant that the cleaning and shaping of root canals is the single most important step in endodontics, and he outlined five important design objectives for every case:

1. The preparation of the root canal should be a "continuously tapering funnel" from the canal orifice to the apical terminus.
2. The diameter of the funnel shape should at any point be narrower towards the apex and wider as it approaches the pulp chamber.
3. The canal preparation shape must follow all curvature present in the naturally occurring anatomy of the root canal spaces.

4. There must not be transportation of the apical foramen with respect to the root surface of the apex and the alveolar bone.
5. During canal preparation, the size of the apical foramen should be kept as minimal as feasible.

As well as four biologic objectives:

1. Procedures should be confined to the roots themselves.
2. Necrotic debris should not be forced beyond the foramina.
3. All tissues should be removed from the root canal space.
4. Sufficient space for intracanal medicaments and irrigation should be created. (1)

Historical Perspective of Endodontic Instruments

Traditionally these instrumentation objectives have been achieved using stainless steel hand files, reamers, and broaches. The use of files in endodontics dates back to the mid 1800s when Edward Maynard developed the first endodontic files (14). He crafted these instruments by notching round wires; initially from watch springs and later from piano wires, into files that were capable of removing pulp tissues and debris from teeth. It was not until 1915 that K-file instruments were developed by the Kerr company. K-files are still the most commonly used stainless steel hand files in endodontics (15). Stainless steel hand file techniques including the step-back technique (16), the anti-curvature technique (4), the step-down technique(17) and the balanced force technique (12) have all been advocated in order to fulfill the instrumentation objectives proposed by

Schilder. The common theme in all of these techniques is to reduce iatrogenic errors while effectively shaping the root canal system.

One of the drawbacks of using stainless steel endodontic instruments is that as the size of the file increases in the sequence of enlarging the root canal during instrumentation, the stiffness of the file also increases (18). This is particularly problematic in curved canals because as the file navigates around the curvature, restoring forces attempt to return the instrument back to its original, straight shape when it is used in a filing motion. This has been shown to lead to procedural errors such as canal transportation, apical zipping, canal ledges, and strip perforations (3, 4, 19). Canal transportation is an undesirable error during instrumentation in which the canal preparation deviates from the original canal anatomy (5). This is troublesome because it can lead to undebrided areas of the canal space as the preparation deviates from the original anatomy. In addition, it also causes a thinning of the canal wall on the side of the tooth that the canal transportation occurs, particularly in molar teeth, where anatomical studies have shown that the thickness of root dentin in furcation areas of mandibular molars can be as thin as 1.2 mm (6). If the transportation of the canal moves towards the furcation, it may result in a perforation of the lateral aspect of the root (strip perforation), which may compromise the prognosis of the tooth.

Introduction of NiTi Instruments

In 1960 a novel alloy, nickel-titanium, was developed in Silver Springs, Maryland at the United States Naval Ordinance Laboratory by William Buehler (20). It is for this reason that NiTi is sometimes referred to as NITINOL, where Ni stands for Nickel, Ti stands for Titanium, and NOL stands for Naval Ordnance Laboratory. Nickel-titanium (NiTi) when present in a one-to-one atomic ratio is a unique alloy because it possesses superelasticity and shape memory effect (20). A game-changing breakthrough in endodontic instrumentation was brought about in 1988 when Harmeet Walia fabricated endodontic files from NiTi orthodontic arch wires (7). These NiTi files were revolutionary because they exhibited two to three times more flexibility, and were more resistant to torsional fracture when compared to equivalent stainless steel files. Due to these favorable characteristics of NiTi alloy, it was found that NiTi files could be used in continuous rotatory motion in an engine driven handpiece in order to mechanically prepare curved root canals (18). The elastic nature of NiTi rotary files has greatly reduced the iatrogenic errors associated with stainless steel files. The use of NiTi rotary files has become the standard of care for instrumentation of the root canal system in modern endodontics because they are more flexible (7), have the ability to stay more centered within the canal (8), and cause less canal transportation (9) when compared to stainless steel hand files.

Over the last two decades NiTi endodontic instruments have seen exponential growth in the marketplace. The NiTi instrument designs and metallurgical processing have gone through several generations of change, all with the hope of providing the clinician with an efficient and safe instrument for preparing the root canal space. The first generation of widely available NiTi instruments were developed by Dr. John McSpadden in 1992 (18). These files possessed a 0.02 taper, and were associated with file breakage problems clinically. Two years later in 1994, Dr. Ben Johnson broke the mold of 0.02 tapered instrument design when he introduced the first greater taper instruments, the ProFile 0.04 and 0.06 tapered instrument series (18). These instruments feature what is now thought of as a "classical" design for NiTi files because they feature U-shaped grooves in the files with flat areas next to each groove known as "radial lands". The radial lands allow for the file to stay centered in the canal space, while the file prepares the canal walls through a passive planing action. Collectively, Dr. McSpadden and Dr. Johnson are considered the fathers of NiTi rotary files, and they have helped push the art and science of endodontic instrumentation into the modern era.

First generation NiTi endodontic instruments were similar in that they all possessed passive cutting radial, fixed tapers over the entire length of the file, and required a large number of files in order to complete their preparation goals. Towards the end of the 1990s, the second generation of NiTi endodontic instruments became available in the marketplace (18). This generation of instruments differs from the previous generation in that they have actively cutting edges on the files without radial lands, and generally require fewer instruments in a series in order to complete the preparation goals. The most notable instrument series from this generation of NiTi files is the ProTaper (Dentsply Tulsa) rotary file series. This file is unique because it is the first instrument to have variable tapers of increasing and decreasing size within a single file. The ProTaper series of files is based on a system of six files: the first three files are designed for the initial enlarging and shaping of the canal, while the last three files are designed for finishing and completing the apical enlargement of the canal. Another notable instrument series from this generation of NiTi files is the K3 (SybronEndo) rotary file series. This file differs from first generation instruments because it features a positive rake angle, or cutting angle of the file flute edges, whereas all previous generations of files had a neutral or slightly negative rake angle (18). The idea of the positive rake angle design is that it helps to improve the cutting efficiency of the instrument making the instrument cut in a more active fashion versus the passive planning action of the neutral/negative rake angle instruments.

The next leap in technology of NiTi endodontic instruments is marked by improvements in the NiTi metallurgy, which represents the third generational change in NiTi files. By using heat treatments (thermal processing) of NiTi it is possible to adjust the transition temperatures of the NiTi alloy itself, which results in a file that has higher resistance to stress and fatigue (18). Starting in 2007, several new files were introduced that utilized thermal processing in order to improve the crystalline microstructure of the NiTi alloy within the file. Highlighted examples from this generation of NiTi rotary instruments include ProFile GT Series X (GTX; Dentsply Tulsa), ProFile Vortex and Vortex Blue (Dentsply Tulsa), K3XF (SybronEndo), and Twisted Files (TF; SybronEndo). First to the market in 2007 was the introduction of M-wire by Dentsply Tulsa. M-wire is produced by undergoing a series of heat treatments to the NiTi file blanks before the file is machined into its finally geometry. ProFile GTX, ProFile Vortex, and Vortex Blue are all produced using this modified M-wire NiTi. Vortex Blue instruments are particularly unique because they undergo even further proprietary heating treatments that render the final instrument with a blue hue. This blue color is a titanium oxide layer on the surface of the file, which is a result of the proprietary thermomechanical process (18). The blue oxide layer of the Vortex Blue instruments is proposed to help improve the cutting efficiency and wear resistance over the M-wire instruments of ProFile Vortex (21).

Later in 2008, SybronEndo was the first manufacturer to introduce a NiTi instrument that was made by plastic deformation called the Twisted File (18). By thermally processing the NiTi, SybronEndo is able to alter the state of the NiTi alloy into the so-called R-phase of NiTi. Once the NiTi alloy is in the altered R-phase it allows the instrument to be twisted into its final geometry instead of being ground and machined into its final state like all other files in the marketplace. The Twisted File instruments are produced owning three unique features: the use of the R-phase heat treated NiTi alloy, twisting of the NiTi alloy instead of being ground, as well as a proprietary surface conditioning treatment of the file (22). The resulting advantages of the Twisted File instruments is their improved flexibility and improved resistance to file fracture due to the lack of machining defects in the flutes of the file that may unnecessarily weaken the file during its clinical application (22).

Another advancement in file design in 2011 by SybronEndo was the update of the K3 instruments to the newer K3XF series. K3XF instruments are identical to the previous K3 instruments in overall shape, but differ in that they undergo a proprietary R-phase heating treatment after the files are machined into their final shape (18). In a study comparing K3 with K3XF instruments it was shown that the R-phase heat treatment of the K3XF files provides superior cyclic fatigue resistance without any decline in the torsional or ultimate strength of the instruments when compared to the original K3 files (23).

Up until the late 2000's almost all of the NiTi instruments were designed to be used in a continuously rotating motion in an engine driven handpiece. The fourth generation of NiTi endodontic instruments is marked by the deviation from this rotary motion with the introduction of NiTi instruments that are designed to be used in a reciprocation style of motion (18). Reciprocation is defined as any repetitive backward and forward motion. The idea of reciprocation itself is not necessary a new one in endodontics as the Giromatic endodontic handpiece has been around since 1958 (18). The Giromatic handpiece utilized stainless-steel files and reciprocated them in the preparation of canal spaces in equal 90^o clockwise (CW) and 90^o counterclockwise (CCW) movements. Over time the reciprocating angles have been changed to smaller degrees of reciprocation movement angles (equal 30^o) CW/CCW movements and the handpiece is still available in the marketplace but has been renamed, the M4 (SybronEndo) handpiece. More recently in 2008, Dr. Ghassan Yared described a novel application of reciprocation movement in endodontic instrumentation in which he identified two unique unequal CW/CCW angles that allowed him to use a single ProTaper instrument (F2: size 25/0.08) to ideally instrument and entire canal system from start to finish (11). This idea sparked the introduction in 2011 of two reciprocation NiTi instrument series, WaveOne (Dentsply Tulsa) and Reciproc (VDW), which both utilize the reciprocation concept set forth by Dr. Yared and also take advantage of a single file shaping protocol to complete root canal preparation objectives (18). The geometry of WaveOne instruments are based on a modified design of the ProTaper instrument series except that they have a reversed helical geometry and they are coupled with a proprietary reciprocating motor. The WaveOne motor is set to move the instruments in a specific reciprocation movement where the CCW engaging angle is five times greater than the CW disengaging angle. This allows the file to advance apically in the canal space in a CCW direction, which is designed to be set below the elastic limit of the WaveOne files. Therefore, after three complete cycles of reciprocation the WaveOne file completes a 360^{o} rotation. It is important to note that the WaveOne file system and specific motor are designed to instrument the root canal space in an overall CCW direction, which is opposite to every other file system available on the market. It hypothesized that this specification is intended so that no other NiTi file system is capable of being used in the particular manner in which WaveOne files are designed to be used. Although the WaveOne instrument series is designed to utilize a single file instrumentation technique, it is available in three file sizes in order to address a wide range of different naturally occurring root canal anatomies. The three files available in the WaveOne system are named Small (size: 21/0.06), Primary (size: 25/0.08) and Large (size: 40/0.08). The unique design and reciprocation instrumentation movement of WaveOne files allows them to safely prepare any give canal space that has an adequate glide path preparation to its terminus (24).

At the same time that the WaveOne instrument was released in the United States, the Reciproc (VDW) reciprocating file system was introduced to the European markets. The Reciproc instrument series possesses many similarities to the WaveOne set of instruments, but differs mainly in the cross sectional design and as well as the sizes of the three instruments available (18). Whereas the WaveOne instruments are based on the ProTaper instrument design, the Reciproc instruments are based on another instrument from the VDW manufacturer, Mtwo, which features a S-shaped cross-sectional design. The three files available in the Reciproc system are regressive in taper and are named: R25 (size: 25/0.08) for smaller canals, R40 (size: 40/0.06) for medium canals, and R50 (size: 50/0.06) for larger canals. The Reciproc file system also has a proprietary reciprocating motor, which operates in a CCW dominate direction analogously to the WaveOne reciprocation motor.

The most recently released NiTi instrument in this generation of files is the TF Adaptive system (SybronEndo), which was brought to market in 2013. The TF Adaptive instruments are based on the Twisted File (SybronEndo) instrument series and for all intents and purposes have identical geometry and metallurgical property as the TF files. The innovation in the TF Adaptive file system is that it aims to take advantage of both continuous rotary movement and reciprocating movement through the use of Adaptive Motion featured in the dedicated Elements motor (25). SybronEndo designed Adaptive Motion, which utilizes a patented, undisclosed algorithm that automatically adapts and changes the file motion based upon the stress placed on the instrument while in use (26). When the TF Adaptive instrument is in the canal and is under little or no stress, the file will operate in an interrupted continuous rotary motion, in the CW direction with no backward CCW motion (600^{o} CW/0^{o} CCW). This allows the instrument to cut more efficiently, and remove more debris since it is essentially functioning in a manner similar to traditional rotary files. Once the TF Adaptive instrument experiences an increase in stress, the motor will change ("adapt") and operate in a reciprocation motion, with specifically designed CW and CCW reciprocating angles. These reciprocation angles vary and are designed to adapt to the changes in the increasing or decreasing stresses applied to the file (examples of varying angles: 550° CW/10° CCW, 500° CW/20° CCW, 450° CW/30° CCW, 400° CW/40° CCW, 370° CW/50° CCW) (25). This "adaptive" reciprocation mode helps to reduce the fatigue on the instrument when the stress applied is greatest, while also maintaining cutting efficiency when not under stress, effectively adapting to the most favorable cutting motion for the given anatomical complexities the file encounters during canal preparation.

Unlike the two other reciprocation systems, TF Adaptive is not designed as a single instrument file series. There are six available TF Adaptive instruments and they are grouped into two series based upon small (SM) sized canals and medium–large (ML) sized canals. The deciding factor between the two groups of instruments is upon initial canal scouting whether a sized #15 K-type hand file fits tightly or loosely. The file sizes available within the small pack are SM1, SM2, and SM3 which correspond to file sizes 20/0.04, 25/0.06, and 35/0.04 respectively. The file sizes available within the medium – large pack are ML1, ML2, and ML3 which correspond to file sizes 25/0.08, 35/0.06, and 50/0.04 respectively. The manufacturer advocates that the TF Adaptive file system, not being based on a single instrumentation series, allows for greater variations in natural anatomy to be effectively treated using this file system, especially when compared to the other reciprocation file systems available on the market.

The last file in the fourth generation of NiTi instruments that deviates from the traditional rotary instrument sequence is the self-adjusting file (SAF; ReDent-Nova) (18). The SAF is designed as a hollow cylindrical file that is made up of latticework of 120-micron thick NiTi with a slightly abrasive surface (27). This flexible hollow file is available in either a 1.5 or 2.0mm diameter and is designed to be compressible once it is inserted into the canal space. The file then expands once in the canal in order to return to its original geometry, thereby adapting to the natural anatomy of the canal shape. If the canal is round it will assume a round shape, if the canal is oval, flat or irregular in any fashion it will likewise assume that shape as well. The SAF is intended to be used in a transline (in and out) vibrating handpiece that is also capable of delivering irrigation to the root canal space while it is preparing the canal. The abrasive surface of the SAF, as well as the in and out grinding motion, promotes a uniform three-dimensional removal of dentin throughout the canal preparation. One of the purported advantages of the SAF is that unlike traditional NiTi rotary files that have a tendency for canal transportation and impart a specific shape to the prepared canal, the SAF simply enlarges the existing canal and retains the original canal anatomy (27).

The latest generation of NiTi endodontic instruments that define the fifth generation of NiTi files' advancement is unique in that the instruments are designed so that the center of mass and/or the center of rotation are offset (18). All previous generations of rotary NiTi instruments are made with a centered core in cross section and therefore when used in continuous rotational motion remain centered and uniform while the file is spinning. By offsetting the center of mass/rotational design of the instrument the file produces a wave-like pattern of motion along the length of the file while spinning. The aim of this wave-like motion is that the file is constantly engaging and disengaging the canal wall along the length of the file, reducing the overall engagement of the file and stresses between the file and the canal wall (18). The most notable system from this generation of files is the ProTaper Next (PTN; Dentsply Tulsa), which is the successor to the ProTaper series. The PTN files are manufactured using M-wire NiTi, feature variable tapers within a single file, have a patented rectangular cross section (versus the triangular cross section of the previous ProTaper), and are designed with the offset design unique to the fifth generation of instruments. The PTN files are available in five sizes: X1 (size: 17/0.04), X2 (size: 25/0.06), X3 (size: 30/0.07), X4 (size: 40/0.06), X5 (size: 50/0.06). The manufacturer of the PTN files claims that the wave-like pattern of motion created due to the offset design of the files creates a swaggering effect of the file that helps to reduce the amount of engagement and stress on the file (18). This reduces the screw in effect that can be problematic for traditional NiTi rotary files, which can lead to an increase in undue torque on the file and potentially fracture of the file itself.

NiTi Instrument Complications

The advancement of endodontic instrumentation through the use of NiTi instruments has helped to reduce procedural errors. NiTi rotary files have become the standard of care for preparation of the root canal system in endodontics because they are more flexible (7), have the ability to stay more centered in the canal (8), and cause less canal transportation (9) when compared to stainless steel hand files. Despite these advantages, rotary NiTi files are not without their complications, and one of the biggest concerns is fracture or separation of the NiTi instrument within the canal during treatment. This complication is problematic because the instrument may not be able to be removed from the canal and could prevent access to the apical extent of the root canal for complete debridement and obturation procedures (28). The exact reason for NiTi instrument facture cannot always be determined and is a process that results from a culmination of various effects; the most critical factors being operator experience, instrument geometry, and root canal morphology (18). The mechanism by which NiTi instruments fracture occurs by one or a combination of two ways: either by torsional and/or flexural fatigue. Torsional fracture occurs when part of the instrument becomes locked in the canal while the shank of the instrument continues to rotate. If the elastic limit of the NiTi file is exceeded when the instrument is locked in the canal then the instrument will fracture. Flexural (or cyclic) fatigue occurs when an instrument continually rotates around a curve, which over time causes extension and compression forces to accumulate in the instrument. This can lead to work hardening of the NiTi alloy and can ultimately result in fracture of the instrument (29).

Reciprocation Instrumentation

In 2008, Dr. Yared described a novel approach to NiTi instrumentation, which utilizes a reciprocating movement of unequal CW and CCW cutting angles versus purely rotating movement of NiTi files in order to overcome the complication of torsional fracture (11). The reciprocating movement aims to reduce this risk by engaging the file in a cutting motion, and then immediately disengaging it in a non-cutting motion. The cutting/engaging motion is designed to be below the elastic limit of the file, so that torsional fatigue is minimized or avoided all together. Since the elastic limit of the file is theoretically never met, this may lead to less or no instrument fracture. The NiTi reciprocating concept is based on the balanced force hand filing technique, which was employed using flexible hand files in a specific CW and CCW sequence in order to prepare curved canals (12). This technique was shown to be effective at negotiating even the most severely curved canals with large hand files in order to accomplish apical preparations while maintaining the original canal shape (30).

Dr. Yared also recommended the single use of NiTi instruments due to the growing concern related to cross-contamination associated with the inability to effectively remove prions from endodontic instruments through routine sterilization procedures (11). Consequently, he described a technique utilizing a single F2 ProTaper instrument that was able to complete canal preparation objectives with a combination of CW and CCW reciprocating movement. This novel canal preparation technique was applauded for two reasons: first, the reciprocating movement was safer due to the avoidance of torsional fatigue; and second, the ability to complete canal preparations with a single file allowed for a more cost effective way to practice single use file protocols thereby eliminating the risks associated with prion cross-contamination.

Advantages of Reciprocation Instrumentation

One of the key advantages of reciprocating motion is that it reduces the effects of torsional fatigue on the instrument, which thereby increases the cyclic fatigue life of the instrument when compared to instruments used in rotational motion (31). This ultimately leads to a safer endodontic instrumentation because file fracture is avoided or the time required before the instrument fractures is prolonged. Many recent articles have substantiated that instruments used in reciprocating motion have a higher cyclic fatigue resistance when compared to instruments used in continuous rotary motion (32-35). Specifically, in a study by Pedulla et al., 4 different NiTi rotary instruments were compared for cyclic fatigue life using the commercially available WaveOne and Reciproc motors versus continuous rotational movement motor. This study showed that all instruments unanimously resulted in a significantly higher cyclic fatigue resistance when run in either of the two reciprocating motors (34). For this reason, reciprocating motion may be an appealing alternative to traditional rotary motion in an effort to reduce undesired instrument failures.

Disadvantages of Reciprocation Instrumentation

One of the many reported advantages of NiTi rotary instrumentation over SS hand file instrumentation is that the action of the rotary motion augers debris up and out of the canal space minimizing the amount of debris that is extruded into the apical tissues (36, 37). Extrusion of debris, which may include dentin chips, necrotic pulp tissues, microorganisms, and intracanal irrigants, may cause increased inflammation, post-operative pain, and a delay in healing of the apical tissues after endodontic therapy (38). Given that instruments used in reciprocal motion move in a back and forth manner, debate exists as to whether or not this motion may cause an increase in the amount of debris extrusion during instrumentation procedures, which may translate into inflammation and pain clinically. An article by Burklein and Schafer demonstrated that there was a significant increase in the amount of apically extruded debris with reciprocating file systems WaveOne and Reciproc when compared to two similar rotary instrument systems (39). On the other hand, a different study compared ProTaper F2 instrumentation in rotary motion and reciprocation motion and found no significant difference in the amount of apically extruded debris between the two instrumentation motions (40).

Another ongoing debate in the reciprocation literature involves the alleged induction of dentin damage or cracks in dentin resulting from reciprocating instrumentation techniques. An article by Burklein et al. in 2013 initiated this debate when they reported that reciprocating file systems generated more cracks in dentin, especially in the apical region of the tooth, when compared to continuous rotary file systems (41). This finding raised concern because dentin cracks may lead to larger fractures in the root dentin, or vertical root fracture, which dooms the prognosis of the tooth. Recently, two articles have been released which refute the initial claims by Burklein et al. De-Deus et al. studied crack propagation using micro-CT imaging, a nondestructive technique, in extracted teeth, and found no differences between reciprocating file systems and rotary file systems (42). Another study aimed at addressing the topic of crack propagation used an *in situ* cadaver model in order to determine whether or not these cracks may occur when a tooth in present in a jaw with a periodontal ligament. The results of this study found that microcracks were present in all groups and that there was no correlation with respect to the type of instrumentation, reciprocation or hand filing, and the presence of cracks (43).

Clinical Studies Involving Reciprocation Instrumentation

Due to the relatively recent nature of commercially available reciprocating file systems, only a few clinical studies have been completed assessing the outcomes of these instruments. Given that reciprocating file systems have been reported to have a longer resistance to cyclic fatigue when compared to rotary file systems in vitro, Cunha et al. reported on a clinical study of 2,215 treated canals over an 18-month period where they assessed the rate of instrument separation using the WaveOne file system. They found a file separation incidence of 0.13% for the WaveOne file system, which was determined to be an acceptably low clinical rate for file separations (44).

Another clinical aspect of reciprocating instrumentation that has been evaluated was to compare whether there is any significant differences in the ability of rotary instruments or reciprocating instruments in removing endotoxins and microorganisms from the canal spaces of teeth in vivo. A study comparing two rotary file systems and two reciprocating file systems found equal effectiveness between both instrumentation movement techniques in their ability to remove endotoxins and microorganisms (45). This study is important because it not only demonstrated that the reciprocating file systems were equivalent to rotary file systems at removing endotoxins and microorganisms, but that they were also able to accomplish this despite the reciprocating file systems only utilizing a single file for complete instrumentation compared a full sequence of rotary files.

Considering the debate that exists in the literature regarding increased apical extrusion of debris when using reciprocating instruments compared to rotary instruments, a clinical study was designed in order to determine if apical extrusion would result in more post-operative pain and whether this was clinically significant or not. Gambarini et al. assessed ninety patients who had undergone root canal therapy using TF, TF Adaptive, or WaveOne instrumentation techniques by a postoperative pain scale questionnaire. The results of the study were interesting in that there was a statistical difference in the amount of post-op pain between WaveOne and TF, but not between TF Adaptive and TF (25). The findings from this study supported that reciprocating file systems have the potential to cause more apical debris extrusion, which may be related to more post-operative discomfort. Although, not all reciprocating file systems are identical, and the TF Adaptive system, which operates in more of a rotary fashion when reciprocation is not needed, may cause less debris extrusion and thus less post-operative pain.

Specific Aims

1. To assess the shaping abilities of three different NiTi file systems.
2. To determine whether using rotational movements compared to reciprocal movements have any impact on shaping abilities of the NiTi files.
3. To assess the time required to complete canal preparations using three NiTi file systems using rotational movements compared to reciprocal movements.

Hypothesis

The null hypotheses of this study is that there will be 1) no differences in shaping abilities between any of the three NiTi file systems; 2) no differences in shaping abilities between either of the instrumentation movements (rotation versus reciprocation); and 3) time required to complete canal preparations will not differ between any of the groups.

Materials and Methods

Preparation of the Samples

One hundred twenty-eight ISO size #15, 0.02 tapered, S-shaped Endo Training Resin Blocks (Dentsply Maillefer, Tulsa, OK) were used in this study. Prior to experimental instrumentation of the resin blocks, each block was indexed with two cylindrical drilled holes above and below the canal space to a uniform depth of 5 mm, which corresponded to the depth of the canal space within the block. The indices served two important functions: first, they allowed for optimal focusing of the canal space when recorded images of the blocks pre- and post-instrumentation were taken using a stereomicroscope; second, they allowed for superimposition of the pre- and post-instrumentation images in order to facilitate measurements of the canal preparations. In order to standardize the placement of the indices into the resin blocks, a custom aluminum jig was fabricated which held each block firmly in the same position while the indices were placed. The custom jig featured a guide on the backside of the block that limited the depth of the bur within the block to 5 mm. The same bur was used to index all of the resin blocks, and the diameter of the bur was 2.36 mm. The resultant indices in the blocks were standardized, uniform, and crisp in appearance, which aided in their intended purpose.

Black India ink (Higgins, Leeds, MA) was injected into the canal space within each resin block with a tuberculin syringe. Each block was then mounted on a secure platform, with white background, in the same custom jig used for indexing the blocks, at 90 degrees perpendicular to the objective lens of an Olympus MVX10 stereomicroscope

(Olympus America, Melville, NY). Pre-instrumentation images were acquired using the dedicated computer software (MicroSuite Five, Olympus America, Melville, NY) with an Olympus DP71 CCD Camera (Olympus America, Melville, NY) attached to the microscope at 40x magnification. The images were saved in .jpg format at a resolution of 4080 x 3072 at 300dpi.

Classification of the Samples

The resin blocks were individually numbered from 1 to 120. Eight blocks were reserved as negative controls, which received no experimental instrumentation and were used to verify the reliability of the superimposition of the pre- and post-instrumentation images in the software program used to preform the measurement analysis of the samples. The 120 numbered resin blocks were then randomly assigned to six groups (20 blocks per group) using a computer aided random numbering service (www.random.org). The six experimental groups were divided according to the instrument type and motion of instrumentation as follows:

Group 1 (N = 20): K3XF in continuous rotational movement
Group 2 (N = 20): K3XF in reciprocal movement
Group 3 (N = 20): TF in continuous rotational movement
Group 4 (N = 20): TF in reciprocal movement
Group 5 (N = 20): PTN in continuous rotational movement
Group 6 (N = 20): PTN in reciprocal movement

Instrumentation of the Samples

All instruments were visually inspected prior to use with a dental operating microscope at 8x magnification (Global Surgical Corporation, Saint Louis, MO) in order to determine if any inherent defects were present in the instruments. No defects were found in any of the instruments used in the study. Each instrument was only used in the preparation of one simulated canal in one resin block sample in order to mimic single patient use clinically.

A random sampling of twelve of the resin blocks was used in order to measure the working length of the simulated s-shaped canal within the resin blocks. The average working length (WL), from the orifice of the canal to the apical terminus of the resin block, was determined to be 16.5mm. In order to assure that all instruments were used at the exact same WL, all of the instruments were placed in a Lexicon Endo-Block (Dentsply Tulsa, Tulsa, OK) at the same 16.5mm measurement place. Once the instrument was stable, the rubber stopper on each file was lowered flush with the top of the block and a ring of visible light cured flowable composite resin (3M ESPE Filtek Supreme Ultra Flowable Restorative, Saint Paul, MN) was placed and light cured on top of the rubber stopper. This step assured that during instrumentation procedures the stopper would not accidentally slide up the file shaft and allow for over instrumentation of the simulated canal, as well as standardized the exact same WL for all files used during canal preparations.

All simulated canals were initially checked for patency prior to preparation procedures using a #10 K-type FlexoFile (Dentsply Maillefer, Tulsa, OK), which was passed 1mm beyond the established WL in order to confirm patency of the canal space. The irrigation solution used throughout the entire preparation sequence for all samples was tap water delivered in a BD Luer-Lok Tip syringe (BD, Franklin Lakes, NJ) with a 30 gauge Max-i-Probe (Dentsply RINN, Tulsa, OK) irrigating needle. Adequate glide path preparations were standardized in all simulated canals using #10, 15, and 20 K-type FlexoFiles (Dentsply Maillefer, Tulsa, OK) in an ascending order using a combination of watch-winding and balanced force techniques. Once the glide path preparations were completed, the experimental instrumentation procedures were performed on the samples according to the group that they were randomly assigned.

Group 1: K3XF in Continuous Rotational Movement (n=20)

The canal preparations for group 1 were completed using rotational movement with K3XF instruments (manufacturer recommended setting: 350 RPM, 300 g-cm torque) in the Sybron Elements torque-controlled motor (SybronEndo, Orange, CA). The preparation sequence began with a 20/0.06 size file that was advanced in the canal until resistance was met or the maximum preset torque value was reached, at which point the file movement was stopped by the torque-controlled motor. The file was then removed, the flutes were cleaned and the canal was irrigated using water. This sequence was repeated until the 20/0.06 file reached the WL. The canal was irrigated and recapitulated using a #15 K-type hand file. The same sequence as the 20/0.06 file was repeated using a 25/0.06 size file until it reached WL. Once the final canal preparation of 25/0.06 was achieved, the canal was thoroughly irrigated with water to ensure that it was free of debris.

Group 2: K3XF in Reciprocal Movement (n=20)

The canal preparations for group 2 were completed using reciprocal movement with K3XF instruments (TF Adaptive setting) in the Sybron Elements torque-controlled motor (SybronEndo, Orange, CA). The preparation sequence began with a 20/0.06 size file that was advanced in the canal until resistance was met or the maximum preset torque value was reached, at which point the file movement was stopped by the torque-controlled motor. The file was then removed, the flutes were cleaned, and the canal was irrigated using water. This sequence was repeated until the 20/0.06 file reached the WL. The canal was irrigated and recapitulated using a #15 K-type hand file. The same sequence as the 20/0.06 file was repeated using a 25/0.06 size file until it reached WL. Once the final canal preparation of 25/0.06 was achieved, the canal was thoroughly irrigated with water to ensure that it was free of debris.

Group 3: TF in Continuous Rotational Movement (n=20)

The canal preparations for group 3 were completed using rotational movement with TF instruments (manufacturer recommended setting: 500 RPM, 400 g-cm torque) in the Sybron Elements torque-controlled motor (SybronEndo, Orange, CA). The preparation sequence began with a 25/0.06 size file that was advanced in the canal until resistance was met or the maximum preset torque value was reached, at which point the file movement was stopped by the torque-controlled motor. The file was then removed, the flutes were cleaned and the canal was irrigated using water. This sequence was repeated until the 25/0.06 file reached the WL. The canal was irrigated and recapitulated using a #15 K-type hand file. Once the final canal preparation of 25/0.06 was achieved, the canal was thoroughly irrigated with water to ensure that it was free of debris.

Group 4: TF in Reciprocal Movement (n=20)

The canal preparations for group 4 were completed using reciprocal movement with TF instruments (TF Adaptive setting) in the Sybron Elements torque-controlled motor (SybronEndo, Orange, CA). The preparation sequence began with a 25/0.06 size file that was advanced in the canal until resistance was met or the maximum preset torque value was reached, at which point the file movement was stopped by the torque-controlled motor. The file was then removed, the flutes were cleaned and the canal was irrigated using water. This sequence was repeated until the 25/0.06 file reached the WL. The canal was irrigated and recapitulated using a #15 K-type hand file. Once the final canal preparation of 25/0.06 was achieved, the canal was thoroughly irrigated with water to ensure that it was free of debris.

Group 5: PTN in Continuous Rotational Movement (n=20)

The canal preparations for group 5 were completed using rotational movement with PTN instruments (manufacturer recommended setting: 300 RPM, 520 g-cm torque) in the Sybron Elements torque-controlled motor (SybronEndo, Orange, CA). The preparation sequence began with a X1 (17/0.04 size) file that was advanced in the canal until resistance was met or the maximum preset torque value was reached, at which point the file movement was stopped by the torque-controlled motor. The file was then removed, the flutes were cleaned and the canal was irrigated using water. This sequence was repeated until the X1 file reached the WL. The canal was irrigated and recapitulated using a #15 K-type hand file. The same sequence as the X1 file was repeated using a X2 (25/0.06 size) file until it reached WL. Once the final canal preparation of X2 (25/0.06 size) was achieved, the canal was thoroughly irrigated with water to ensure that it was free of debris.

Group 6: PTN in Reciprocal Movement (n=20)

The canal preparations for group 6 were completed using reciprocal movement with PTN instruments (TF Adaptive setting) in the Sybron Elements torque-controlled motor (SybronEndo, Orange, CA). The preparation sequence began with a X1 (17/0.04 size) file that was advanced in the canal until resistance was met or the maximum preset torque value was reached, at which point the file movement was stopped by the torque-controlled motor. The file was then removed, the flutes were cleaned and the canal was irrigated using water. This sequence was repeated until the X1 file reached the WL. The canal was irrigated and recapitulated using a #15 K-type hand file. The same sequence as the X1 file was repeated using a X2 (25/0.06 size) file until it reached WL. Once the final canal preparation of X2 (25/0.06 size) was achieved, the canal was thoroughly irrigated with water to ensure that it was free of debris.

Once all the preparations of the sample blocks were completed, Black India ink (Higgins, Leeds, MA) was re-injected into the canal space within each resin block with a tuberculin syringe. Each block was then re-mounted on a secure platform at 90 degrees perpendicular to the objective lens of an Olympus MVX10 stereomicroscope (Olympus

America, Melville, NY). Post-instrumentation images were acquired using the dedicated computer software (MicroSuite Five, Olympus America, Melville, NY) with an Olympus DP71 CCD Camera (Olympus America, Melville, NY) attached to the microscope at 40x magnification. The images were saved in .jpg format at a resolution of 4080 x 3072 at 300dpi.

Preparation of the Images for Measurement and Analysis

For each sample block, the pre-instrumentation image and post-instrumentation image were superimposed and standardized using Adobe Photoshop CS6 Extended (Adobe Systems Incorporated, San Jose, CA). The images were opened in Photoshop using the scripts tool, 'load files into stack' with the 'automatically align source images' option selected. This allowed for the images to be aligned and superimposed over one another into two 'Layers'. The alignment of the two layers was visually confirmed using the alignment of the indices on the resin blocks. The pre-instrumentation image layer color was adjusted using the 'Invert' tool and the opacity level was decreased to 50%. This allowed for the visualization of the canal shape in the pre- and post-instrumentation images to become clearly evident. The two image layers were then combined to form a single image.

Once the superimposition image was created the image was standardized so that measurements could be made and compared across all samples. To accomplish this, the diameter of the lower right index was recorded using the calibrated measurement tool in the computer software of the Olympus MVX10 stereomicroscope (Olympus America, Melville, NY). The same diameter measurement was recorded using the ruler tool in Photoshop, which then allowed for a custom measurement scale to be set in Photoshop. The custom measurement scale that was used to standardize all measurements across all the samples was 1,083 pixels = 2.3995 mm (a ratio of 451.34 pixels to 1.0 mm). After the custom measurement scale was set, all the images were cropped to a standardized size. The standardized size for each image included cropping the left edge of the image at the terminus of the canal space of the resin block, the right edge of the image was then measured to be exactly 8.0 mm from the left edge and was cropped. This resulted in a uniform 8.0 mm of canal space for which all measurements could be taken and compared between all the samples (see *Figure 1*). All standardized sample images were saved with their corresponding sample ID for measurements to be made by the evaluators.

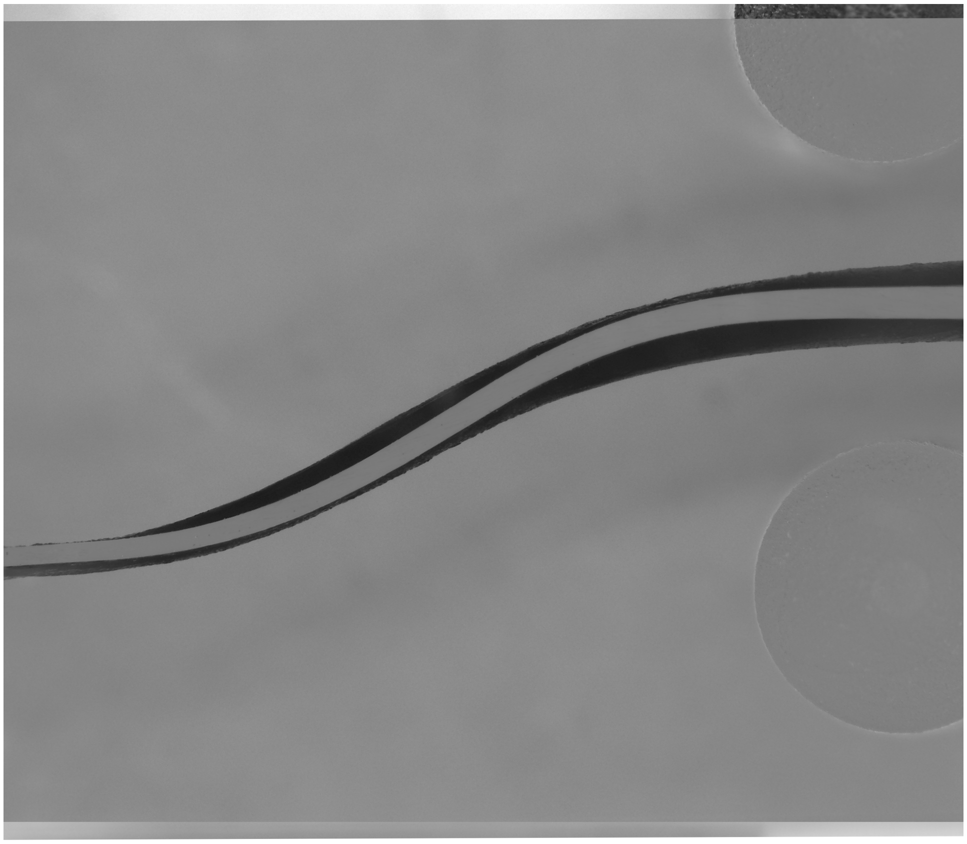


***Figure 1**: Superimposition image: pre-instrumentation canal (gray) and post-instrumentation canal (black).*

Measurement of Area Differences

Measurements were completed by two independent, blinded evaluators using the calibrated ruler tool in Adobe Photoshop CS6 Extended. Both evaluators were trained and calibrated on the Adobe Photoshop measurement protocol, and all sample images were viewed on the same computer workstation at 2560 x 1600 resolution on a HPZR30w LCD monitor (Hewlett-Packard, Palo Alto, CA). Both evaluators were blinded as to which group each sample belonged to that they were performing the measurements on.

Area measurements were recorded in Photoshop utilizing the ‘Magic Wand Tool’. Once the standardized image for each sample was opened, the desired area to be measured was selected using the magic wand tool. The specific area was closely inspected by enlarging the image (up to 400%) in order to evaluate the accuracy of the selection. If the area selection was inaccurate, the selection could be remade or modified using the ‘Quick Selection Tool’. After the designated area was selected, the ‘Record Measurement’ button was selected in the analysis section of Photoshop, which automatically computed the area for the selection in mm^2 using the preset custom measurement scale. The evaluators recorded the area measurements in mm^2 to the nearest 0.0001 level for each sample in a separate spreadsheet. The average of the two evaluators’ measurements were used for all calculations and statistical analyses. Inter-evaluator reliability was assessed by taking the difference between the two evaluators measurements for all seven area regions (Table 7). The overall difference between the two evaluators was 0.0043, which was determined to be an acceptably low inter-evaluator value. The intra-evaluator reliability was also assessed by having each evaluator return 1-2 weeks after all initial measurements were completed and re-measure six randomly chosen samples. In order to assess intra-evaluator reliability these measurements were compared to the original measurements, and an average was taken for each evaluator (Table 8). Both evaluators had an overall intra-evaluator of 0.0031, which was determined to be an acceptably low intra-evaluator value.

Area change measurements between the pre-instrumented canal space and the post-instrumented canal space were recorded for every sample in seven defined regions.

The seven regions measured were defined as follows: 1) total area difference above the pre-instrumented canal (*Figure 2*); 2) apical half of the area difference above the pre-instrumented canal (*Figure 3*); 3) coronal half of the area difference above the pre-instrumented canal (*Figure 4*); 4) total area difference below the pre-instrumented canal (*Figure 5*); 5) apical half of the area difference below the pre-instrumented canal (*Figure 6*); 6) coronal half of the area difference below the pre-instrumented canal (*Figure 7*); 7) total area difference above and below the pre-instrumented canal (*Figure 8*).

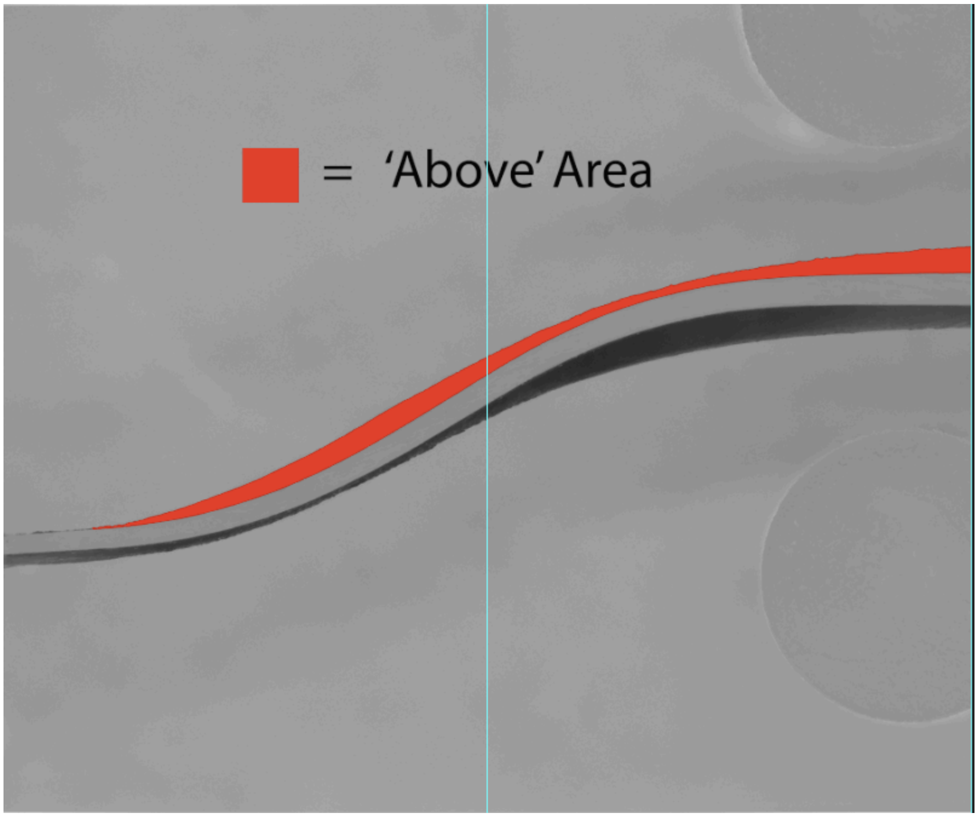


Figure 2: *Above area difference.*

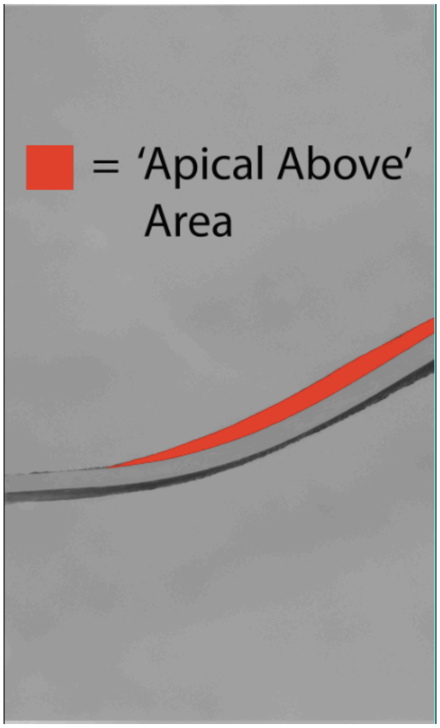


Figure 3: *Apical Above area difference.*

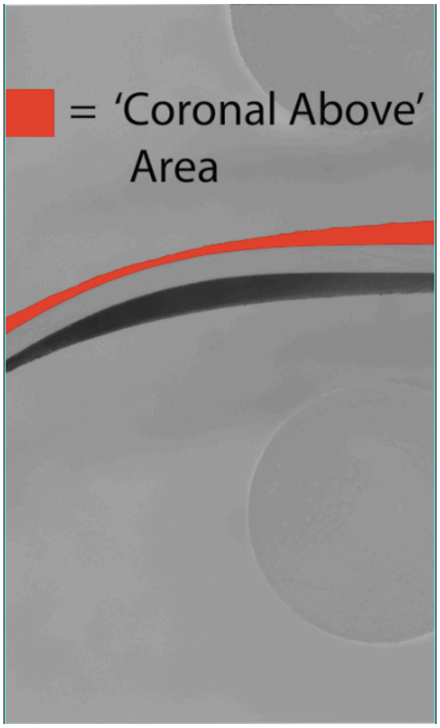


Figure 4: *Coronal Above area difference.*

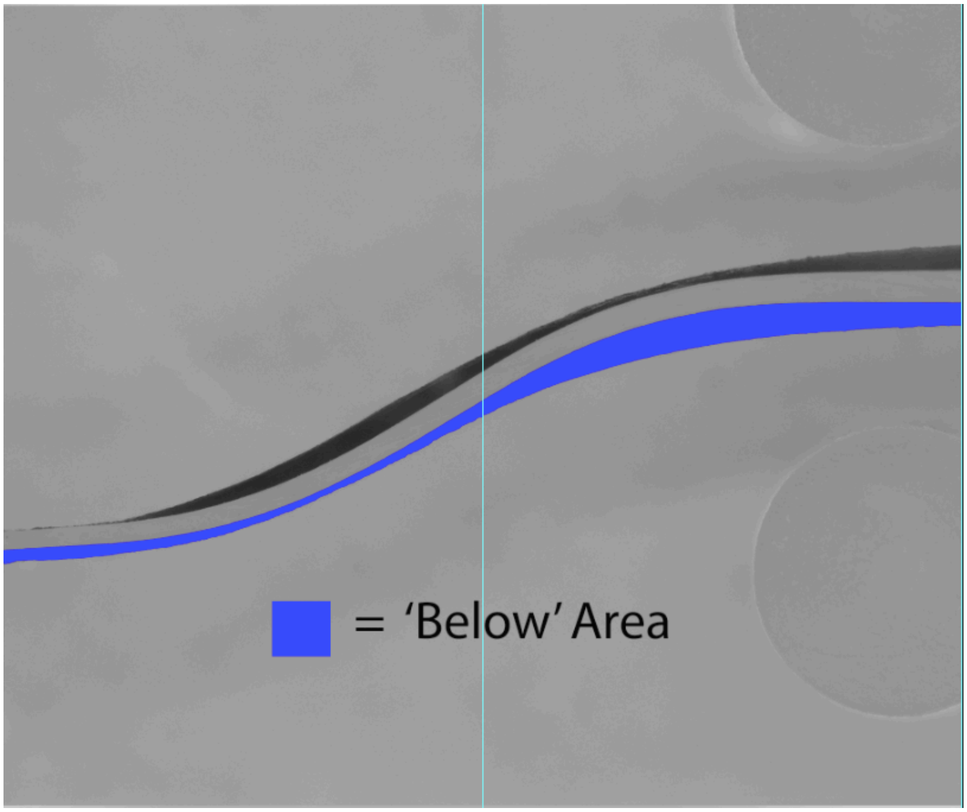


Figure 5: *Below area difference.*

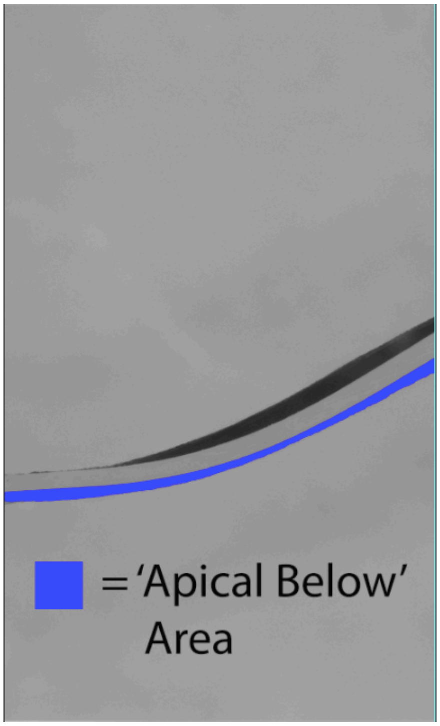


Figure 6: *Apical Below area difference.*

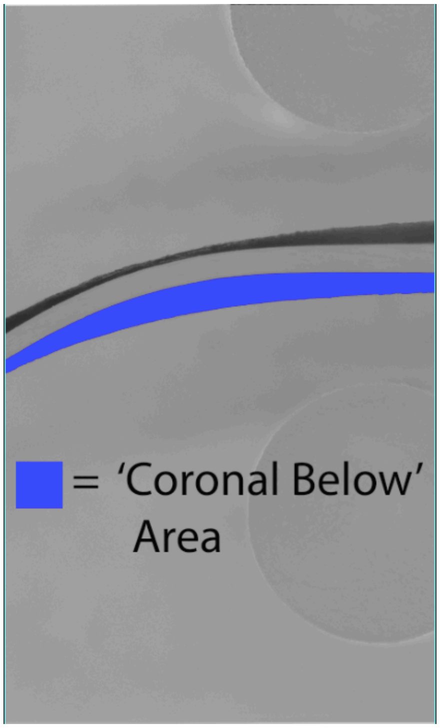


Figure 7: *Coronal Below area difference.*

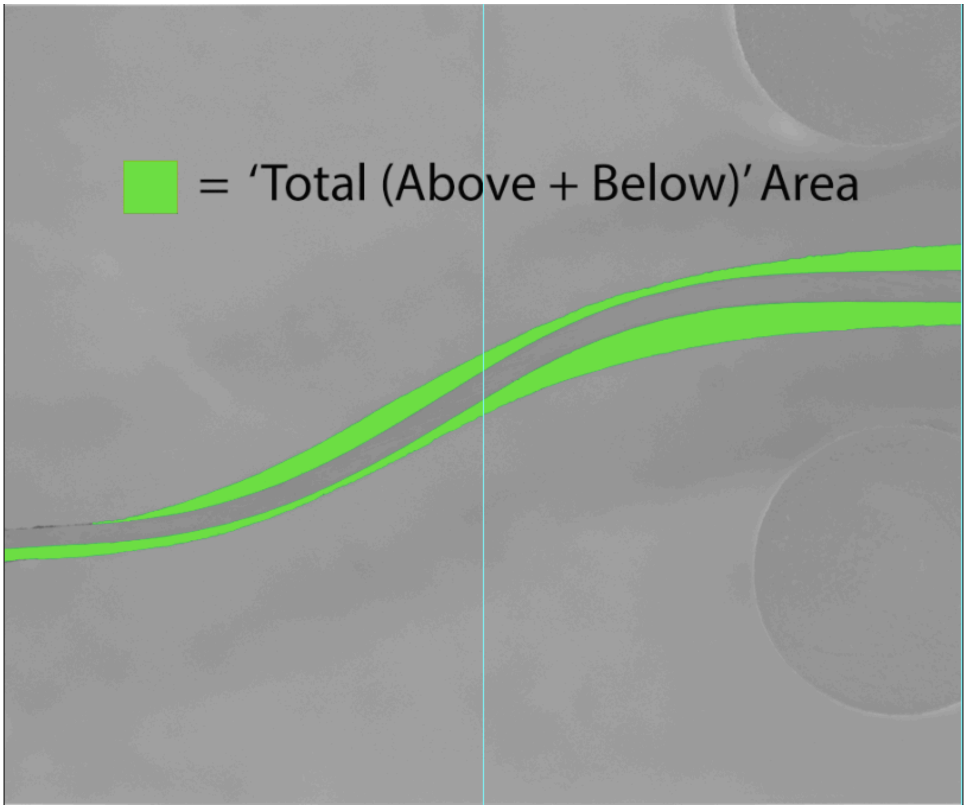


Figure 8: *Total (Above + Below) area difference.*

Measurement of Time to Complete Canal Preparations

The time to complete canal preparations was recorded for each sample. Once adequate glide path preparations had been completed on each sample block and prior to experimental instrumentation procedures, a digital stopwatch was used in order to record the amount of time that was required to complete the entire canal preparation for each sample. The average times for each group were used for statistical analysis.

Statistical Analysis

Descriptive statistics (mean, standard deviation, median, minimum, and maximum) were calculated for each area difference outcome by group. Outcomes were compared using a two-way analysis of variance (ANOVA) with an interaction term. The instrument and the type of movement were the two factors. If the interaction was statistically significant ($p < 0.05$), the type of movement was compared for each instrument. If the instrument factor was statistically significant, pairwise comparisons were made using a Tukey-Kramer adjustment for multiple comparisons. P values < 0.05 were considered statistically significant. Inter- and intra-evaluator measurer errors were also assessed. SAS V9.3 (SAS Institute, Inc., Cary, NC) was used for the statistical analysis.

Results

The statistical outcomes for each area region by instrument type, movement type, statistical significance level, and pairwise comparisons between groups can be found in Table 6. The descriptions of the outcome for each surface area are detailed below.

<u>'Coronal Above' outcome:</u>

A main effect for the instrument ($p<0.0001$) was found to be statistically significant for the 'Coronal Above' outcome. The average area was highest for K3XF (Mean= 0.62, Standard Deviation= 0.04). PTN was (M= 0.57, SD= 0.05) and TF (M=0.47, SD=0.05) was the lowest. All pairwise comparisons were statistically significant ($p<0.0001$). The main effect of movement was also significant ($p=0.0021$). The average area was higher for rotary (M= 0.57, SD= 0.08) when compared to reciprocation (M= 0.54, SD= 0.08). The interaction effect was non-significant ($p=0.9750$) indicating that the differences in movement did not depend on instrument.

<u>'Apical Above' outcome:</u>

A main effect for the instrument ($p=0.2540$) was found to be not statistically significant for the 'Apical Above' outcome. The average area was similar for all instruments: K3XF (Mean=0.50, Standard Deviation=0.06), PTN (M=0.51, SD=0.06), TF (M=0.53, SD=0.08). The main effect of movement was also not statistically significant ($p=0.2799$). The average area for rotary and reciprocation were similar: reciprocation (M=0.51, SD=0.06), rotary (M=0.52, SD=0.08). The interaction effect for this outcome was statistically significant ($p=0.0005$), and the difference was found between the TF rotary and TF reciprocation groups (p=0.0002), with TF reciprocation average area being less than TF rotary area.

‘Above’ outcome:

A main effect for the instrument (p<0.0001) was found to be statistically significant for the ‘Above’ outcome. The average area was highest for K3XF (Mean=1.14, Standard Deviation=0.10). PTN was (M= 1.09, SD=0.09) and TF (M=1.01, SD=0.12) was the lowest. The main effect of movement was not statistically significant (p=0.0506). The average area for rotary and reciprocation were similar: reciprocation (M=1.06, SD=0.14), rotary (M=1.10, SD=0.09). The interaction effect for this outcome was statistically significant (p=0.0073), and the difference was found between the TF rotary and TF reciprocation groups (p=0.0005), with TF reciprocation average area being less than TF rotary area.

‘Coronal Below’ Outcome:

A main effect for the instrument (p=0.1034) was found to be not statistically significant for the ‘Coronal Below’ outcome. The average area was similar for all instruments: K3XF (Mean=1.00, Standard Deviation=0.07), PTN (M=1.00, SD=0.09), TF (M=0.97, SD=0.11). The main effect of movement was statistically significant (p=0.0376). The average area was higher for rotary (M= 1.00, SD= 0.08) when compared to reciprocation (M= 0.97, SD= 0.10). The interaction effect for this outcome was also statistically significant (p<0.0001), and the differences were found between the TF rotary and TF reciprocation groups (p<0.0001), and between the K3XF rotary and K3XF reciprocation groups (p=0.0004). The TF reciprocation average area was less than the TF rotary area; whereas, the K3XF rotary average area was less than the K3XF reciprocation area.

‘Apical Below’ Outcome:

A main effect for the instrument (p<0.0001) was found to be statistically significant for the ‘Apical Below’ outcome. The average area was highest for K3XF (Mean= 0.41, Standard Deviation= 0.04). PTN was (M= 0.34, SD= 0.05) and TF (M=0.31, SD=0.05) was the lowest. All pairwise comparisons were statistically significant (p<0.0001 for all except p=0.0280 for PTN vs TF). The main effect of movement was also significant (p=0.0400). The average area was higher for rotary (M= 0.36, SD= 0.05) when compared to reciprocation (M= 0.34, SD= 0.07). The interaction effect was non-significant (p=0.0953) indicating that the differences in movement did not depend on instrument.

‘Below’ Outcome:

A main effect for the instrument (p<0.0001) was found to be statistically significant for the ‘Below’ outcome. The average area was highest for K3XF (Mean= 1.41, Standard Deviation= 0.09). PTN was (M= 1.36, SD= 0.10) and TF (M=1.28, SD=0.15) was the lowest. The main effect of movement was also significant (p=0.0392). The average area was higher for rotary (M=1.37, SD= 0.09) when compared to reciprocation (M= 1.33, SD= 0.15). The interaction effect for this outcome was also statistically significant (p<0.0001), and the differences were found between the TF rotary and TF reciprocation groups (p<0.0001), and between the K3XF rotary and K3XF reciprocation groups (p=0.0047). The TF reciprocation average area was less than the TF rotary area; whereas, the K3XF rotary average area was less than the K3XF reciprocation area.

<u>‘Total (Above + Below)’ Outcome:</u>

A main effect for the instrument (p<0.0001) was found to be statistically significant for the ‘Total (Above + Below)’ outcome. The average area was highest for K3XF (Mean= 2.55, Standard Deviation= 0.15). PTN was (M= 2.45, SD= 0.13) and TF (M=2.28, SD=0.26) was the lowest (*see Figure 9*).

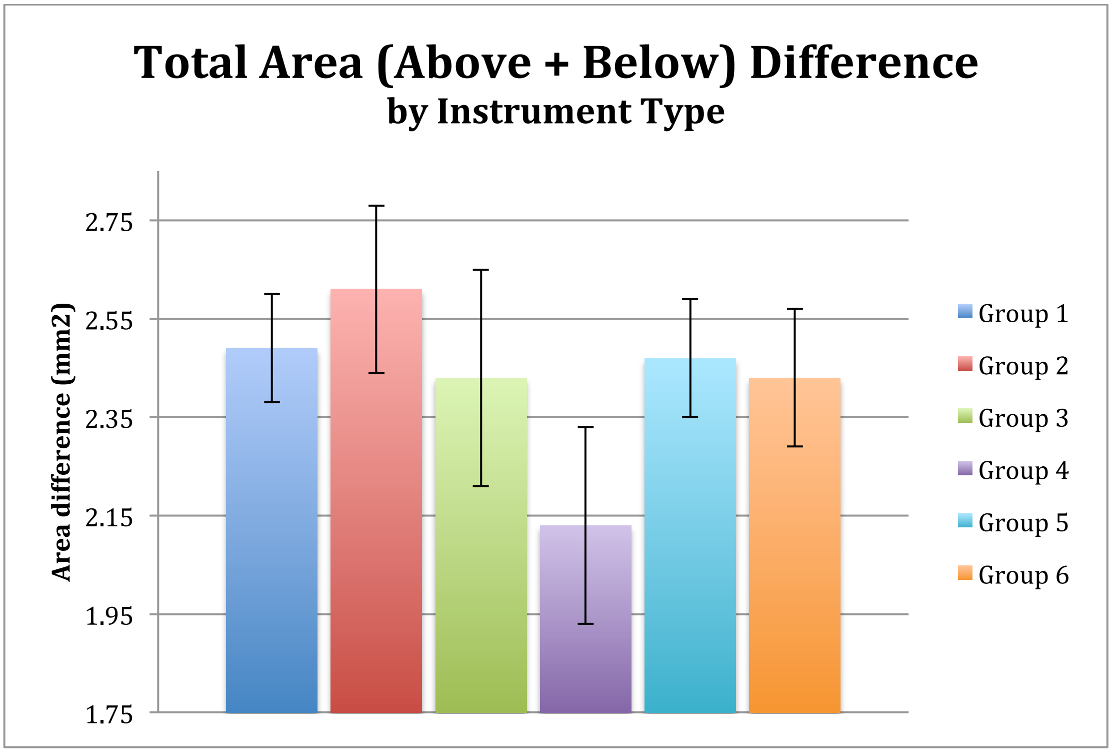


Figure 9: *Total (Above + Below) area difference results (by instrument type).*

The main effect of movement was also significant (p=0.0153). The average area was higher for rotary (M=2.46, SD= 0.15) when compared to reciprocation (M=2.39, SD=0.26) (*see Figure 10*).

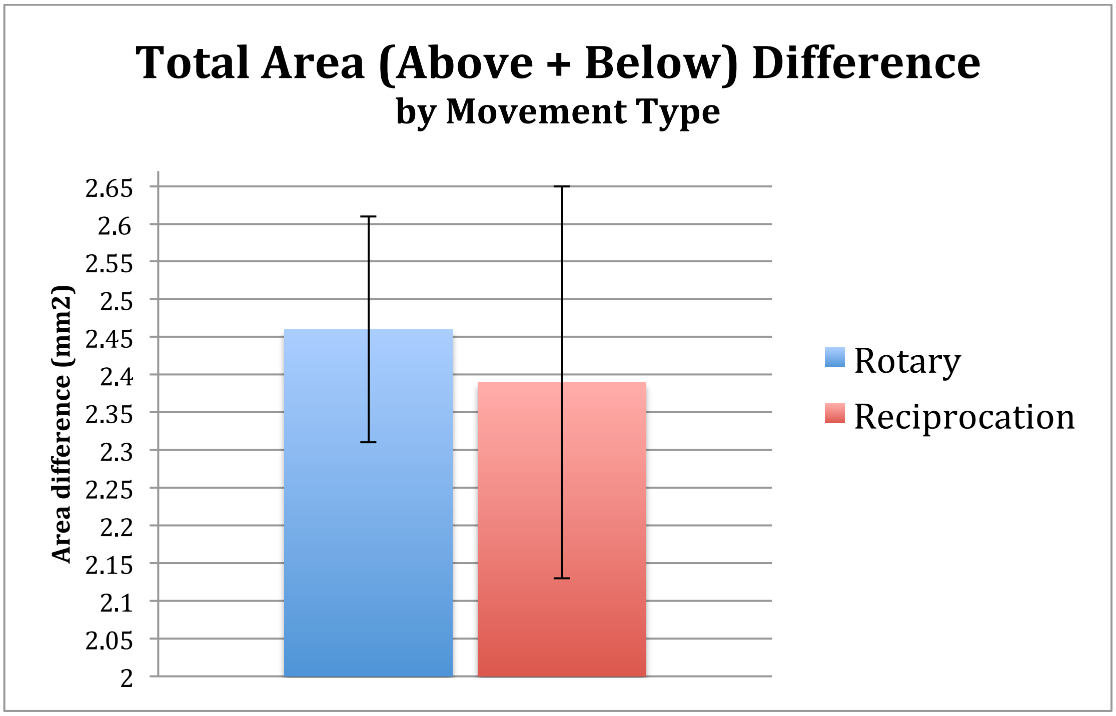


Figure 10: *Total (Above + Below) area difference results (by movement type).*

The interaction effect for this outcome was also statistically significant (p<0.0001), and the differences were found between the TF rotary and TF reciprocation groups (p<0.0001), and between the K3XF rotary and K3XF reciprocation groups (p=0.0233). The TF reciprocation average area was less than the TF rotary area; whereas, the K3XF rotary average area was less than the K3XF reciprocation area (*see Figure 9*).

‘Time’ Outcome:

There was a statistically significant difference (p<0.0001) in time to complete canal preparation between the K3XF rotary and reciprocation groups. The K3XF reciprocation group (Mean= 72.34, Standard Deviation= 23.24) was significantly faster than the K3XF rotary group (M= 99.40, SD= 13.68). No significant differences were found between the TF and PTN groups in either reciprocation or rotary movements (*see Figure 11*).

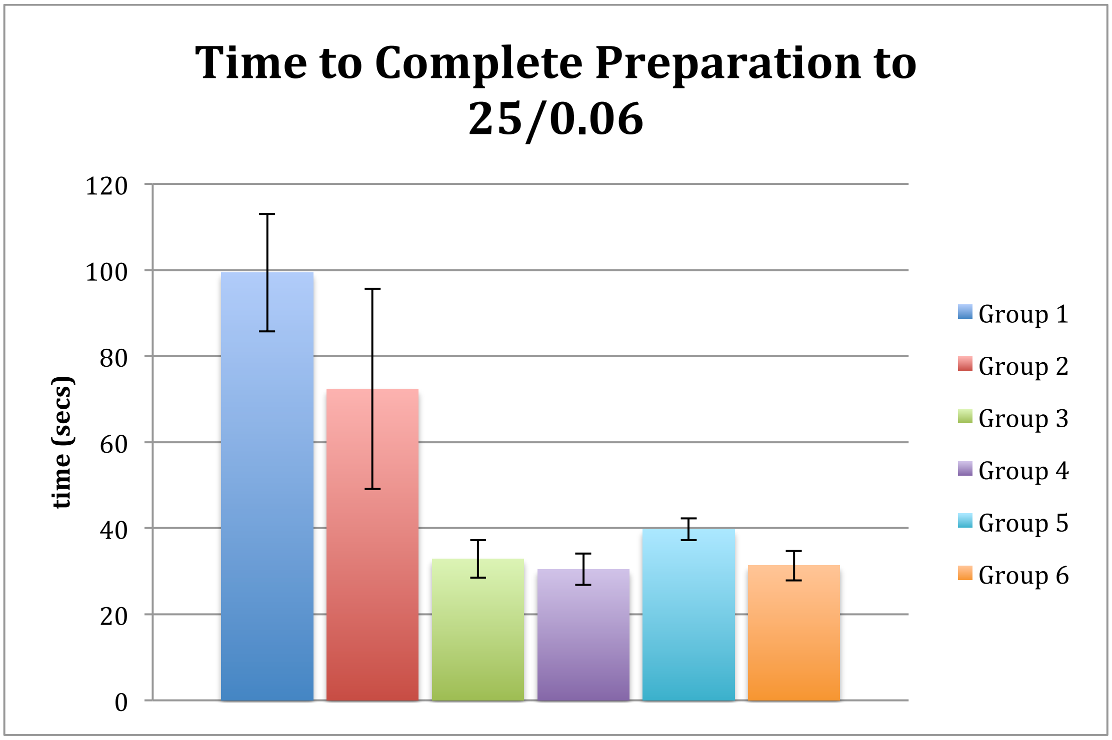


Figure 11: *Time results to complete preparation to 25/0.06.*

<u>Negative Control:</u>

All eight of the negative control samples yielded no area differences between the pre- and post-instrumentation images in any of the seven defined measurement regions. This confirmed the validity of the alignment, standardization, and measurement tool in the Adobe Photoshop CS6 software program.

Discussion

One of the major determinants of quality canal shaping ability of an endodontic instrument is its ability to stay well centered within the root canal space and not produce iatrogenic errors such as canal transportation (46). Numerous methodologies exist to assess the shaping ability and transportation of endodontic instruments. In this study, canal shaping ability was assessed using an S-shaped resin block model where area differences in the amount of canal transportation in the pre- and post-instrumented canals were assessed according to instrument and movement type. Seven defined regions were measured for area differences. The lower the resultant area difference between the pre- and post-instrumentation images in these defined area can be interpreted as an endodontic instrument with superior shaping abilities due to the fact that it has caused less canal transportation, and therefore better maintained the original canal anatomy. Studying the canal shaping abilities and characteristics of different file systems is important because it provides the clinician with valuable insight into the ever-expanding endodontic armamentarium available so that they can make informed decisions regarding the most effective and safe instruments to complete root canal preparation objectives.

In this study, two file systems that were designed for use in rotary instrumentation, and one file system that has been designed for use in rotary and reciprocation instrumentation were chosen for comparisons. The selection of these three file systems represents a diverse range of modern endodontic instrument designs as well as the latest advances in NiTi metallurgy. K3XF represents a third generational type of NiTi instrument. This file is a radially landed, has a constant taper throughout the length of the file, and is made with the heat-treated NiTi. TF differs in that it is an active, non-landed file, is not machined into it's final geometry, but rather "twisted" into form using heat, and is made using the R-phase NiTi. PTN differs in that it represents the latest, fifth generational type of NiTi instruments, it has an offset center of rotation, it is rectangular in cross section, has variable tapers throughout individual files as well as between files in the system, and is made of M-wire NiTi.

Resin blocks were utilized in this study to assess instrument shaping abilities because they provide a number of advantages over extracted teeth. First, resin blocks can be standardized in canal curvature and length, which is inherently variable in extracted teeth. Second, the clear resin allow for direct visualization during instrumentation procedures and allows for imaging of the final canal preparations by direct measures as well. Lastly, dentin from extracted teeth, especially when derived from many different donors, has been shown to vary in hardness by as much as 25% (47). This can be problematic in endodontic instrumentation research because it hinders the ability to compare one sample to another when such variability exists in the samples naturally. Therefore, Dr. Weine in 1975, developed simulated root canals in resin blocks in order to standardize research models instead of using extracted teeth with wide disparities, as well as to facilitate canal preparation technique research (3). These resin models have been validated in a study, which demonstrated that there were no significant differences found in the shape prepared by hand filing techniques in extracted teeth compared with simulated canals in resin blocks (48).

While there are many advantages to using simulated canals in resin blocks, there are several factors that should be considered when interpreting results from an instrumentation study using these models. First, the evaluation of the canal preparations is limited to the longitudinal plane of the canal, which only represents two-dimensions when in reality endodontic instruments are preparing the canal in three-dimensions. Second, the resin blocks lack the physical characteristics of human dentin, most notably with respect to microhardness. When compared to root dentin in natural teeth, the hardness of resin blocks is approximately half of that found in dentin (48). The significance of this is that instrumentation studies using resin blocks are more likely to represent a greater amount of deviations or canal transportations than may be actually occurring when instrumenting natural teeth. Lastly, resin blocks have different thermal properties than dentin (46). Endodontic rotary instruments generate a significant amount of frictional heat during instrumentation procedures, which may be capable of melting the resin of the blocks in some instances. This represents a scenario that is vastly different from clinical applications of endodontic instruments as this is not an occurrence observed in teeth clinically.

Within the limitations of this study, the null hypothesis that there will be no differences in shaping abilities, instrumentation movement type, and time to complete canal preparations between any of the three NiTi file systems has to be rejected. Statistical analysis showed there were significant differences between NiTi file systems, instrumentation movement type, as well as time to complete canal preparations. With respect to overall shaping abilities, the TF file system performed better the PTN file system followed by the K3XF file system in all defined areas measured except for the 'Apical Above' and 'Coronal Below' areas. These results are similar to a study by Hashem et al. where the TF file system was found to produce less canal transportation and remain more centered in a curved canal model, ultimately leading to superior shaping ability when compared to other comparable rotary file systems (49). The authors justified these results in that the unique manufacturing process of the TF file system yields an endodontic instrument that is superior in flexibility to others compared within the study.

Instrumentation movement type had the most pronounced effect between TF in rotary motion and TF in reciprocal motion. The TF file performed the best in reciprocal motion in all defined regions compared to TF in rotary motion. This is likely explained by the fact that the TF file is triangular in cross section and is a non-landed, actively cutting file, which allows the instrument to cut in both the CW and CCW directions of reciprocal motion. The ability of an instrument to cut in the CW and CCW direction was found to be a key characteristic for a file to work efficiently when using in reciprocal motion (31). Interestingly, the K3XF file system performed worse in reciprocal motion in several regions compared to K3XF in rotary motion. The reason for this finding is likely due to the fact that the K3XF file system has more of a passive cutting action with its radial lands, and is designed to cut efficiently in the CW direction, but not when reversed in the CCW direction. The PTN file system produced no significant differences in movement type in any of the defined areas measured. PTN was designed to be used in continuous rotary movement with a unique "swaggering" motion due to its offset center of rotation. The results of this study demonstrate that the unique motion of the PTN has no effect on its shaping abilities whether it is used in continuous rotary or reciprocal motion. This outcome may be explained because the PTN file is also a non-landed, actively cutting file, so it is capable of cutting in CW and CCW motion, but that it has no significant effect on the outcome of its shaping ability.

With respect to the movement type of instrumentation, the results showed that reciprocal motion was better in shaping ability compared to rotary motion in all defined areas except for ‘Apical Above’ and ‘Above’ areas. These results are in accordance with several studies that have found reciprocating file systems to perform as well as, or better, with respect to maintaining the original canal anatomy and producing less canal transportation of curved canals when compared to similar file systems in rotary motion (24, 50, 51).

The time required to complete canal preparations was only statistically different between two groups: the K3XF file system in rotary versus the K3XF file system in reciprocal motion. The K3XF file system in reciprocal motion was capable of completing canal preparations significantly quicker that the K3XF file system in rotary motion. Another study has shown that reciprocating file systems are capable of completing canal preparations in a shorter amount of time when compared to continuous rotary file systems (50). It is interesting to note, in this study the only difference in canal preparation time that occurred between rotary and reciprocation was in the K3XF file system, which performed worse with respect to its shaping ability in reciprocal motion.

Conclusions

Within the limitations of this study, it can be concluded that:

1. In overall shaping abilities, the TF file system performed better than the PTN file system followed by the K3XF file system in a majority of the defined area measured.
2. Instrumentation movement type had the greatest effect between TF in rotary motion and TF in reciprocal motion. The TF file system performed the best in reciprocal motion in all defined regions compared to TF in rotary motion.
3. The results of the movement type of instrumentation, showed that reciprocal motion was better in shaping ability compared to rotary motion in a majority of the defined areas measured.
4. The time required to complete canal preparations was only significantly quicker for the K3XF file system in reciprocal motion versus the K3XF file system in rotary motion.

References

1. Schilder H. Cleaning and shaping the root canal. Dent Clin North Am. 1974;18(2):269-96.

2. Camps J, Pertot W. Relationship between file size and stiffness of stainless steel instruments. Endod Dent Traumatol. 1994;10(6):260-3.

3. Weine FS, Kelly RF, Lio PJ. The effect of preparation procedures on original canal shape and on apical foramen shape. J Endod. 1975;1(8):255-62.

4. Abou-Rass M, Frank A, Glick D. The anticurvature filing method to prepare the curved root canal. J Am Dent Assoc. 1980;101(5):792-4.

5. Peters O. Current challenges and concepts in the preparation of root canal systems: A review. J Endod. 2004;30(8):559-67.

6. Berutti E, Fedon G. Thickness of cementum/dentin in mesial roots of mandibular first molars. J Endod. 1992;18(11):545-8.

7. Walia HM, Brantley WA, Gerstein H. An initial investigation of the bending and torsional properties of nitinol root canal files. J Endod. 1988;14(7):346-51.

8. Esposito PT, Cunningham CJ. A comparison of canal preparation with nickel-titanium and stainless steel instruments. J Endod. 1995;21(4):173-6.

9. Glossen CR, Haller RH, Dove SB, del Rio CE. A comparison of root canal preparations using ni-ti hand, ni-ti engine-driven, and K-flex endodontic instruments. J Endod. 1995;21(3):146-51.

10. Martin B, Zelada G, Varela P, Bahillo JG, Magin F, Ahn S, et al. Factors influencing the fracture of nickel-titanium rotary instruments. Int Endod J. 2003;36(4):262-6.

11. Yared G. Canal preparation using only one ni-ti rotary instrument: Preliminary observations. Int Endod J. 2008;41(4):339-44.

12. Roane JB, Sabala CL, Duncanson MG. The "balanced force" concept for instrumentation of curved canals. J Endod. 1985;11(5):203-11.

13. Kakehashi S, Stanley H, Fitzgerald R. The effects of surgical exposures of dental pulps in germ-free and conventional laboratory rats. Oral surgery, oral medicine, oral pathology. 1965;20:340-9.

14. Grossman L. Endodontics 1776-1976: A bicentennial history against the background of general dentistry. J Am Dent Assoc. 1976;93(1):78-87.

15. Hulsmann M, Peters O, Dummer P. Mechanical preparation of root canals: Shaping goals, techniques and means. Endodontic topics. 2005;10(1):30-76.

16. Mullaney T. Instrumentation of finely curved canals. Dent Clin North Am. 1979;23(4):575-92.

17. Goerig A, Michelich R, Schultz H. Instrumentation of root canals in molar using the step-down technique. J Endod. 1982;8(12):550-4.

18. Haapasalo M, Shen Y. Evolution of nickel–titanium instruments: From past to future. Endodontic topics. 2013;29(1):3-17.

19. Abou Rass M, Frank AL, Glick DH. The anticurvature filing method to prepare the curved root canal. J Am Dent Assoc. 1980;101(5):792-4.

20. Zhou H, Peng B, Zheng Y. An overview of the mechanical properties of nickel–titanium endodontic instruments. Endodontic topics. 2013;29(1):42-54.

21. Ye J, Gao Y. Metallurgical characterization of M-wire nickel-titanium shape memory alloy used for endodontic rotary instruments during low-cycle fatigue. J Endod. 2012;38(1):105-7.

22. Gambarini G, Grande N, Plotino G, Somma F, Garala M, De Luca M, et al. Fatigue resistance of engine-driven rotary nickel-titanium instruments produced by new manufacturing methods. J Endod. 2008;34(8):1003-5.

23. Ha J, Kim S, Cohenca N, Kim H. Effect of R-phase heat treatment on torsional resistance and cyclic fatigue fracture. J Endod. 2013;39(3):389-93.

24. Berutti E, Chiandussi G, Paolino D, Scotti N, Cantatore G, Castellucci A, et al. Canal shaping with WaveOne primary reciprocating files and ProTaper system: A comparative study. J Endod. 2012;38(4):505-9.

25. Gambarini G, Testarelli L, De Luca M, Milana V, Plotino G, Grande N, et al. The influence of three different instrumentation techniques on the incidence of postoperative pain after endodontic treatment. Ann Stomatol. 2013;4(1):152-5.

26. Gergi R, Osta N, Bourbouze G, Zgheib C, Arbab Chirani R, Naaman A. Effects of three nickel titanium instrument systems on root canal geometry assessed by micro-computed tomography. Int Endod J. 2014.

27. Metzger Z, Teperovich E, Zary R, Cohen R, Hof R. The self-adjusting file (SAF). part 1: Respecting the root canal anatomy--a new concept of endodontic files and its implementation. J Endod. 2010;36(4):679-90.

28. Spili P, Parashos P, Messer H. The impact of instrument fracture on outcome of endodontic treatment. J Endod. 2005;31(12):845-50.

29. Sattapan B, Nervo G, Palamara J, Messer H. Defects in rotary nickel-titanium files after clinical use. J Endod. 2000;26(3):161-5.

30. Kyomen S, Caputo A, White S. Critical analysis of the balanced force technique in endodontics. J Endod. 1994;20(7):332-7.

31. Varela-Patino P, Ibanez-Parraga A, Rivas-Mundina B, Cantatore G, Otero X, Martin-Biedma B. Alternating versus continuous rotation: A comparative study of the effect on instrument life. J Endod. 2010;36(1):157-9.

32. De Deus G, Moreira E, Lopes H, Elias C. Extended cyclic fatigue life of F2 ProTaper instruments used in reciprocating movement. Int Endod J. 2010;43(12):1063-8.

33. Gambarini G, Gergi R, Naaman A, Osta N, Al Sudani D. Cyclic fatigue analysis of twisted file rotary NiTi instruments used in reciprocating motion. Int Endod J. 2012;45(9):802-6.

34. Pedulla E, Plotino N, Gambarini G, Rapisarda E. Influence of continuous or reciprocating motion on cyclic fatigue resistance of 4 different nickel-titanium rotary instruments. J Endod. 2013;39(2):258-61.

35. Perez-Higueras J, Arias A, de la Macorra J. Cyclic fatigue resistance of K3, K3XF, and twisted file nickel-titanium files under continuous rotation or reciprocating motion. J Endod. 2013;39(12):1585-8.

36. Reddy S, Hicks M. Apical extrusion of debris using two hand and two rotary instrumentation techniques. J Endod. 1998;24(3):180-3.

37. Kustarci A, Akpinar K, Er K. Apical extrusion of intracanal debris and irrigant following use of various instrumentation techniques. Oral surgery, oral medicine, oral pathology, oral radiology and endodontology. 2008;105(2):257-62.

38. Seltzer S, Naidorf IJ. Flare-ups in endodontics: I. etiological factors. J Endod. 1985;11(11):472-8.

39. Burklein S, Schafer E. Apically extruded debris with reciprocating single-file and full-sequence rotary instrumentation systems. J Endod. 2012;38(6):850-2.

40. De Deus G, Brandao M, Barino B, Di Giorgi K, Fidel R, Luna A. Assessment of apically extruded debris produced by the single-file ProTaper F2 technique under reciprocating movement. Oral surgery, oral medicine, oral pathology, oral radiology and endodontology. 2010;110(3):390-4.

41. Burklein S, Tsotsis P, Schafer E. Incidence of dentinal defects after root canal preparation: Reciprocating versus rotary instrumentation. J Endod. 2013;39(4):501-4.

42. De-Deus G, Silva E, Marins J, Souza E, Neves A, Belladonna F, et al. Lack of causal relationship between dentinal microcracks and root canal preparation with reciprocation systems. - Journal of Endodontics. 2014.

43. Arias A, Lee Y, Peters C, Gluskin A, Peters O. Comparison of 2 canal preparation techniques in the induction of microcracks: A pilot study with cadaver mandibles. J Endod. 2014;40(7):982-5.

44. Cunha R, Junaid A, Ensinas P, Nudera W, da Silveira Bueno C. Assessment of the separation incidence of reciprocating WaveOne files: A prospective clinical study. J Endod. 2014;40(7):922-4.

45. Martinho F, Gomes A, Fernandes A, Ferreira N, Endo M, Freitas L, et al. Clinical comparison of the effectiveness of single-file reciprocating systems and rotary systems for removal of endotoxins and cultivable bacteria from primarily infected root canals. J Endod. 2014 5;40(5):625-9.

46. Shen Y, Cheung G. Methods and models to study nickel–titanium instruments. Endodontic topics. 2013;29(1):18-41.

47. Peyton F, Mahler D, Hershenov B. Physical properties of dentin. J Dent Res. 1952;31(3):366-70.

48. Lim K, Webber J. The validity of simulated root canals for the investigation of the prepared root canal shape. Int Endod J. 1985;18(4):240-6.

49. Hashem A, Ghoneim A, Lutfy R, Foda M, Omar G. Geometric analysis of root canals prepared by four rotary NiTi shaping systems. J Endod. 2012;38(7):996-1000.

50. Burklein S, Hinschitza K, Dammaschke T, Schafer E. 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. Int Endod J. 2012;45(5):449-61.

51. Gergi R, Osta N, Bourbouze G, Zgheib C, Arbab Chirani R, Naaman A. Effects of three nickel titanium instrument systems on root canal geometry assessed by micro-computed tomography. Int Endod J. 2014.

Appendix I

Table 1 - Evaluator #1: The MEANS Procedure

Instrument	Movement	N	Variable	N	Mean	Std Dev	Median	Min	Max
K3XF	Reciprocation	20	Cor_Above	20	0.61	0.04	0.61	0.54	0.67
			Api_Above	20	0.52	0.05	0.51	0.43	0.60
			Above	20	1.13	0.08	1.14	0.99	1.29
			Cor_Below	20	1.04	0.05	1.03	0.96	1.13
			Api_Below	20	0.40	0.04	0.41	0.33	0.47
			Below	20	1.45	0.09	1.46	1.33	1.63
			total	20	2.58	0.14	2.59	2.38	2.86
			Time	10	72.34	23.24	63.76	52.65	117.21
	Rotary	20	Cor_Above	20	0.64	0.05	0.64	0.56	0.72
			Api_Above	20	0.49	0.07	0.50	0.33	0.64
			Above	20	1.13	0.07	1.13	0.95	1.29
			Cor_Below	20	0.95	0.06	0.96	0.81	1.06
			Api_Below	20	0.41	0.04	0.39	0.35	0.50
			Below	20	1.35	0.07	1.34	1.21	1.47
			total	20	2.49	0.11	2.45	2.30	2.74
			Time	10	99.40	13.68	98.83	78.95	123.55
PTN	Reciprocation	20	Cor_Above	20	0.56	0.05	0.57	0.46	0.63
			Api_Above	20	0.52	0.07	0.52	0.40	0.66
			Above	20	1.08	0.10	1.09	0.87	1.27
			Cor_Below	20	1.01	0.07	1.03	0.84	1.10
			Api_Below	20	0.33	0.06	0.33	0.21	0.44
			Below	20	1.36	0.11	1.36	1.12	1.58
			total	20	2.44	0.14	2.43	2.25	2.71
			Time	10	31.30	3.47	31.13	25.96	36.73
	Rotary	20	Cor_Above	20	0.58	0.05	0.58	0.49	0.67
			Api_Above	20	0.51	0.06	0.48	0.44	0.68
			Above	20	1.11	0.09	1.10	0.96	1.36
			Cor_Below	20	1.03	0.05	1.03	0.94	1.11
			Api_Below	20	0.35	0.05	0.35	0.22	0.41
			Below	20	1.37	0.08	1.38	1.20	1.51
			total	20	2.48	0.11	2.47	2.23	2.70
			Time	10	39.69	2.54	39.51	35.60	43.58
TF	Reciprocation	20	Cor_Above	20	0.46	0.05	0.47	0.36	0.54
			Api_Above	20	0.49	0.07	0.48	0.38	0.61
			Above	20	0.95	0.10	0.94	0.78	1.12
			Cor_Below	20	0.91	0.08	0.91	0.73	1.03
			Api_Below	20	0.29	0.04	0.29	0.20	0.40
			Below	20	1.19	0.11	1.18	0.95	1.42
			total	20	2.14	0.19	2.12	1.76	2.44
			Time	10	30.40	3.65	29.77	25.86	37.88
	Rotary	20	Cor_Above	20	0.49	0.04	0.47	0.42	0.59
			Api_Above	20	0.56	0.08	0.58	0.39	0.71
			Above	20	1.06	0.10	1.07	0.89	1.30
			Cor_Below	20	1.04	0.09	1.03	0.90	1.22
			Api_Below	20	0.33	0.04	0.33	0.25	0.39
			Below	20	1.37	0.12	1.38	1.13	1.61
			total	20	2.43	0.21	2.44	2.07	2.91
			Time	10	32.89	4.39	32.58	26.61	43.61

Table 2 - Evaluator #2: The MEANS Procedure

Instrument	Movement	N	Variable	N	Mean	Std Dev	Median	Min	Max
K3XF	Reciprocation	20	Cor_Above	20	0.60	0.03	0.60	0.54	0.66
			Api_Above	20	0.52	0.05	0.52	0.46	0.60
			Above	20	1.17	0.20	1.14	1.05	1.98
			Cor_Below	20	1.04	0.05	1.03	0.96	1.13
			Api_Below	20	0.41	0.04	0.41	0.33	0.49
			Below	20	1.45	0.09	1.44	1.32	1.63
			total	20	2.63	0.22	2.58	2.38	3.41
	Rotary	20	Cor_Above	20	0.63	0.05	0.62	0.56	0.72
			Api_Above	20	0.48	0.07	0.49	0.32	0.64
			Above	20	1.12	0.07	1.11	0.96	1.29
			Cor_Below	20	0.95	0.05	0.96	0.84	1.04
			Api_Below	20	0.40	0.05	0.39	0.32	0.49
			Below	20	1.37	0.08	1.36	1.24	1.55
			total	20	2.49	0.11	2.49	2.31	2.75
PTN	Reciprocation	20	Cor_Above	20	0.55	0.05	0.55	0.46	0.64
			Api_Above	20	0.51	0.06	0.51	0.39	0.65
			Above	20	1.07	0.09	1.08	0.90	1.27
			Cor_Below	20	0.95	0.22	1.01	0.08	1.12
			Api_Below	20	0.33	0.05	0.32	0.25	0.45
			Below	20	1.35	0.11	1.36	1.09	1.53
			total	20	2.42	0.15	2.43	2.16	2.74
	Rotary	20	Cor_Above	20	0.58	0.05	0.58	0.48	0.70
			Api_Above	20	0.50	0.05	0.49	0.44	0.63
			Above	20	1.09	0.08	1.09	0.94	1.28
			Cor_Below	20	1.02	0.05	1.01	0.92	1.11
			Api_Below	20	0.35	0.05	0.36	0.19	0.41
			Below	20	1.37	0.10	1.38	1.13	1.51
			total	20	2.46	0.12	2.42	2.20	2.72
TF	Reciprocation	20	Cor_Above	20	0.46	0.05	0.47	0.36	0.53
			Api_Above	20	0.48	0.07	0.48	0.36	0.60
			Above	20	0.95	0.11	0.95	0.79	1.13
			Cor_Below	20	0.89	0.08	0.89	0.70	1.03
			Api_Below	20	0.29	0.05	0.28	0.19	0.37
			Below	20	1.18	0.12	1.18	0.92	1.38
			total	20	2.13	0.21	2.13	1.73	2.51
	Rotary	20	Cor_Above	20	0.48	0.05	0.48	0.40	0.60
			Api_Above	20	0.57	0.08	0.58	0.40	0.75
			Above	20	1.06	0.11	1.06	0.86	1.31
			Cor_Below	20	1.03	0.10	1.04	0.89	1.21
			Api_Below	20	0.33	0.04	0.34	0.24	0.40
			Below	20	1.37	0.12	1.37	1.15	1.62
			total	20	2.43	0.23	2.40	2.05	2.94

Table 3 – Average of 2 Evaluators: The MEANS Procedure

Instrument	Movement	N	Variable	N	Mean	Std Dev	Median	Min	Max
K3XF	Reciprocation	20	cor_above_a	20	0.60	0.03	0.60	0.55	0.66
			api_above_a	20	0.52	0.05	0.52	0.45	0.60
			above_a	20	1.15	0.12	1.14	1.03	1.59
			cor_below_a	20	1.04	0.05	1.03	0.96	1.13
			api_below_a	20	0.41	0.04	0.41	0.33	0.48
			below_a	20	1.45	0.09	1.46	1.33	1.63
			total_a	20	2.61	0.17	2.58	2.38	3.06
	Rotary	20	cor_above_a	20	0.63	0.05	0.63	0.56	0.71
			api_above_a	20	0.48	0.07	0.49	0.33	0.64
			above_a	20	1.13	0.07	1.12	0.95	1.29
			cor_below_a	20	0.95	0.06	0.97	0.82	1.05
			api_below_a	20	0.41	0.05	0.38	0.34	0.50
			below_a	20	1.36	0.07	1.35	1.23	1.50
			total_a	20	2.49	0.11	2.48	2.35	2.74
PTN	Reciprocation	20	cor_above_a	20	0.56	0.05	0.56	0.46	0.63
			api_above_a	20	0.51	0.07	0.52	0.40	0.66
			above_a	20	1.08	0.09	1.08	0.88	1.27
			cor_below_a	20	0.98	0.11	1.02	0.58	1.11
			api_below_a	20	0.33	0.05	0.33	0.24	0.45
			below_a	20	1.35	0.11	1.35	1.10	1.55
			total_a	20	2.43	0.14	2.42	2.20	2.73
	Rotary	20	cor_above_a	20	0.58	0.05	0.58	0.49	0.69
			api_above_a	20	0.50	0.06	0.49	0.44	0.65
			above_a	20	1.10	0.09	1.09	0.95	1.32
			cor_below_a	20	1.02	0.05	1.02	0.93	1.11
			api_below_a	20	0.35	0.05	0.35	0.20	0.41
			below_a	20	1.37	0.09	1.37	1.16	1.51
			total_a	20	2.47	0.12	2.46	2.22	2.71
TF	Reciprocation	20	cor_above_a	20	0.46	0.05	0.48	0.36	0.54
			api_above_a	20	0.49	0.07	0.48	0.38	0.60
			above_a	20	0.95	0.10	0.94	0.78	1.11
			cor_below_a	20	0.90	0.08	0.90	0.71	1.02
			api_below_a	20	0.29	0.04	0.29	0.20	0.39
			below_a	20	1.18	0.12	1.19	0.94	1.40
			total_a	20	2.13	0.20	2.13	1.74	2.47
	Rotary	20	cor_above_a	20	0.48	0.04	0.47	0.42	0.59
			api_above_a	20	0.57	0.08	0.58	0.39	0.73
			above_a	20	1.06	0.10	1.07	0.88	1.31
			cor_below_a	20	1.04	0.09	1.03	0.89	1.22
			api_below_a	20	0.33	0.04	0.34	0.25	0.39
			below_a	20	1.37	0.12	1.38	1.14	1.62
			total_a	20	2.43	0.22	2.41	2.07	2.93

Table 4 – Average of 2 Evaluators by Instrument: The MEANS Procedure

Instrument	Variable	N	Mean	Std Dev	Median	Min	Max
K3XF	cor_above_a	40	0.62	0.04	0.61	0.55	0.71
	api_above_a	40	0.50	0.06	0.50	0.33	0.64
	above_a	40	1.14	0.10	1.12	0.95	1.59
	cor_below_a	40	1.00	0.07	0.98	0.82	1.13
	api_below_a	40	0.41	0.04	0.40	0.33	0.50
	below_a	40	1.41	0.09	1.39	1.23	1.63
	total_a	40	2.55	0.15	2.53	2.35	3.06
PTN	cor_above_a	40	0.57	0.05	0.57	0.46	0.69
	api_above_a	40	0.51	0.06	0.50	0.40	0.66
	above_a	40	1.09	0.09	1.09	0.88	1.32
	cor_below_a	40	1.00	0.09	1.02	0.58	1.11
	api_below_a	40	0.34	0.05	0.34	0.20	0.45
	below_a	40	1.36	0.10	1.36	1.10	1.55
	total_a	40	2.45	0.13	2.43	2.20	2.73
TF	cor_above_a	40	0.47	0.05	0.48	0.36	0.59
	api_above_a	40	0.53	0.08	0.54	0.38	0.73
	above_a	40	1.01	0.12	1.01	0.78	1.31
	cor_below_a	40	0.97	0.11	0.96	0.71	1.22
	api_below_a	40	0.31	0.05	0.31	0.20	0.39
	below_a	40	1.28	0.15	1.28	0.94	1.62
	total_a	40	2.28	0.26	2.27	1.74	2.93

Table 5 – Average of 2 Evaluators by Movement: The MEANS Procedure

Movement	Variable	N	Mean	Std Dev	Median	Min	Max
Reciprocation	cor_above_a	60	0.54	0.08	0.56	0.36	0.66
	api_above_a	60	0.51	0.06	0.51	0.38	0.66
	above_a	60	1.06	0.14	1.06	0.78	1.59
	cor_below_a	60	0.97	0.10	1.00	0.58	1.13
	api_below_a	60	0.34	0.07	0.34	0.20	0.48
	below_a	60	1.33	0.15	1.35	0.94	1.63
	total_a	60	2.39	0.26	2.42	1.74	3.06
Rotary	cor_above_a	60	0.57	0.08	0.58	0.42	0.71
	api_above_a	60	0.52	0.08	0.50	0.33	0.73
	above_a	60	1.10	0.09	1.10	0.88	1.32
	cor_below_a	60	1.00	0.08	1.00	0.82	1.22
	api_below_a	60	0.36	0.05	0.36	0.20	0.50
	below_a	60	1.37	0.09	1.36	1.14	1.62
	total_a	60	2.46	0.15	2.47	2.07	2.93

Table 6 – Statistical Outcomes: P-values from a two-way ANOVA

Outcome: Area	**Instrument**	**Movement**	**Interaction**
Coronal Above	**<0.0001**	**0.0021**	0.9750
Apical Above	0.2540	0.2799	**0.0005‡**
Above	<0.0001	0.0506	**0.0073±**
Coronal Below	0.1034	0.0376	**<0.0001†**
Apical Below	**<0.0001**	**0.0400**	0.0953
Below	<0.0001	0.0392	**<0.0001***
Total (Above + Below)	<0.0001	0.0153	**<0.0001****
Time	<0.0001	<0.0001	**0.0034*****

P-values from a two-way ANOVA. Non-significant interaction terms were removed from the models.

For 'Coronal Above', all pairwise comparisons for instrument are significant (p<0.0001).

For 'Apical Below', all pairwise comparisons for instrument are significant (p<0.0001 for all except p=0.0280 for PTN vs TF).

‡ Rotary vs Reciprocation for TF: p=**0.0002**; Rotary vs Reciprocation for K3XF: p=0.1089; Rotary vs Reciprocation for PTN: p=0.7144

± Rotary vs Reciprocation for TF: p=**0.0005**; Rotary vs Reciprocation for K3XF: p=0.3747; Rotary vs Reciprocation for PTN: p=0.4694

† Rotary vs Reciprocation for TF: **p<0.0001**; Rotary vs Reciprocation for K3XF: **p=0.0004**; Rotary vs Reciprocation for PTN: p=0.1277

* Rotary vs Reciprocation for TF: **p<0.0001**; Rotary vs Reciprocation for K3XF: **p=0.0047**; Rotary vs Reciprocation for PTN: p=0.5452

** Rotary vs Reciprocation for TF: **p<0.0001**; Rotary vs Reciprocation for K3XF: **p=0.0233**; Rotary vs Reciprocation for PTN: p=0.4213

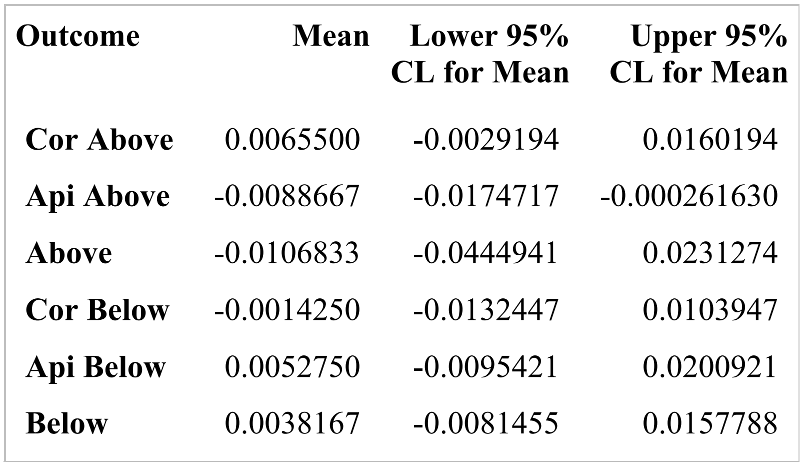
*** Rotary vs Reciprocation for TF: p=0.6272; Rotary vs Reciprocation for K3XF: **p<0.0001**; Rotary vs Reciprocation for PTN: p=0.1052; Groups 1 and 2 are clearly different than the rest.

Table 7 – Inter-Evaluator Reliability Calculations

Outcome	Mean (95% CI)
Coronal Above	0.00592 (0.00234,0.00950)
Apical Above	0.00225 (-0.00074,0.00524)
Above	0.00110 (-0.0130,0.0152)
Coronal Below	0.0178 (0.000953,0.0347)
Apical Below	-0.00014 (-0.00394,0.00367)
Below	-0.00112 (-0.00835,0.00610)
Overall	0.004304 (-0.00316,0.01177)*

*Adjusted for instrument, movement, and outcome with sample id as a random effect.

Table 8 – Intra-Evaluator Reliability Calculations



Outcome	Mean	Lower 95% CL for Mean	Upper 95% CL for Mean
Cor Above	0.0065500	-0.0029194	0.0160194
Api Above	-0.0088667	-0.0174717	-0.000261630
Above	-0.0106833	-0.0444941	0.0231274
Cor Below	-0.0014250	-0.0132447	0.0103947
Api Below	0.0052750	-0.0095421	0.0200921
Below	0.0038167	-0.0081455	0.0157788

Overall: 0.003139 (-0.01749, 0.02377)

Adjusted for instrument, movement, outcome and rater.