Influence of Kinematics of Nickel-Titanium Instruments on Root Canal Preparations of Dental Students –A Micro CT Evaluation

A Thesis
Submitted to
Temple University Graduate Board

In Partial Fulfillment of the
Requirements for the Degree
MASTER OF SCIENCE

By Akshay Keerthy, D.M.D
August 2023

Thesis Approvals:

Dr. Jong Ryul Kim, DMD, PhD, Thesis Advisor, Department of Endodontology, Temple University Kornberg School of Dentistry

Dr. Wanda Gordon, DMD, Department of Endodontology, Temple University Kornberg School of Dentistry

Dr. Santiago Orrego, PhD, Oral Health Sciences Department, Temple University Kornberg School of Dentistry

ABSTRACT

Introduction:

One of the most important steps in endodontic treatment includes the shaping and instrumentation of the root canal system. If not done properly, it may lead to errors including canal transportations and uncentered preparations. Over the last decades, nickel-titanium (NiTi) rotary instruments have enhanced the quality of root canal shaping for clinicians. Currently, two common NiTi rotary instruments, WaveOne Gold and ProTaper Gold, function by two different forms of kinematics: a reciprocating and rotating movement respectively. Currently, preclinical curricula in dental schools do not have a standardized rotary file in which dental students are introduced into endodontics with. This study looks at the use of these two rotary systems by novice sophomore dental students on the quality of their root canal preparations.

Purpose:

This study aims to examine the influence of kinematics of nickel-titanium instruments (reciprocation vs rotation) on the shaping ability, canal transportation and centering ratio, of novice pre-doctoral sophomore dental students and their preference after its use.

Materials and Methods:

Forty two identical pre-accessed mandibular left first molar 3-dimensional printed replicas' mesial canals (TrueTeeth; PlanBDental) were instrumented by 21 novice pre-doctoral sophomore dental students. Each canal was previously hand instrumented to a size #15 K file by a single provider. The students were recruited using a random number generator. The teeth were divided up into 2 groups for each rotary file system being used: ProTaper Gold (PTG) (n=21) and WaveOne Gold (WOG) (n=21). Each student

instrumented both the mesiobuccal (MB) and mesiolingual canals (ML) using each system. The total instrumentation time was recorded. Micro-computed tomography was used to scan the teeth before and after instrumentation. Centering ratios and canal transportation were calculated at the apical, middle and coronal levels. A questionnaire was completed after instrumentation regarding students' perception with a 5-point Likert scale: ease of use, flexibility, cutting efficiency, screwing effect and overall impression.

Conclusion:

Compared to a rotation NiTi file system, reciprocation NiTi file system was preferred by novice sophomore dental students, and it also showed less canal transportation and better centering ability with shorter instrumentation times. Future studies are still needed in order to assess if there are further advantages to training novice dental students with reciprocating rotary systems when learning endodontics, but this study can serve as a framework to answer the question.

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

CHAPTER 1
INTRODUCTION

One of the most important steps, to provide quality care, while performing endodontic treatment includes instrumentation and shaping of the canals. The main goals of endodontic instrumentation include mechanical debridement of the root canal system, facilitating the use of irrigants to the entire canal, and providing a funnel shaped preparation that can be properly obturated. Vyver describes an ideal instrumented root canal as one that results in a continuously tapered funnel-shaped canal that is identical to the original canal anatomy. There have been many changes to what an ideal instrumentation of a root canal system is expected to look like due to the changes of the armamentarium.

Over the past decades, the evolution of the armamentarium that we have as clinicians, in specifically endodontics, has grown tremendously. Beginning in the early 1900s, some of the first true endodontic instruments were brought to the market. These instruments included K-files and K-reamers hand files which were fabricated out of stainless steel. These hand files were solely used in order to properly complete the instrumentation of a root canal system for most of the 20th century until the key addition of Nickel-Titanium (NiTi) rotary instruments were introduced in the mid-1990s.

One of the reasons for the advancements in the armamentarium used in endodontic instrumentation is to achieve methods where clinicians can properly instrument the root canals to an appropriate apical diameter while decreasing the risk for procedural errors. One assessment used in the endodontic literature in order to assess the quality of the instrumentation of root canals is done by evaluating the canal transportation

and the centering ratio values. The 2019 AAE Glossary of Terms defines canal transportation as the “removal of canal wall structure on the outside curve of the canal due to the tendency of files to restore themselves to their original linear shape during canal preparation”. By analyzing the canal transportation, one can measure the deviation from the original canal axis after endodontic instrumentation (Vyver, 2019). The other metric used for assessing the quality of a root canal instrumentation is the centering ratio which incorporates the same values when calculating canal transportation, however, it gives a ratio which helps demonstrate how well centered the instrumentation of the root canal preparation is.

Previous research studies, such as one by Short et al, have shown that the use of rotary instruments during instrumentation leads to having more centered preparations in comparison to those instrumented with stainless steel hand files. More recent NiTi rotary instruments are heat treated and have different temperature dependent crystalline structures which allow them to be much more flexible than their stainless steel predecessors. These advancement in the file technology has allowed the use of NiTi rotary instruments to become much more mainstream for clinicians.

One new innovation that was introduced to the realm of NiTi rotary files was the reciprocating rotary file system in 2003. Reciprocating rotary files were introduced in endodontics as a means to decrease instrument separations and shorten the learning curve for clinicians as they are a one file system. These reciprocating file systems function in a unique kinematic motion than the traditional rotating NiTi rotary files do. These reciprocating rotary files function by cutting in a counter-clockwise fashion for 150 degrees circumferentially and then subsequently reversing to cut 30 degrees in a

clockwise direction. Thus, it takes three complete rotations of both of these steps in order to have the rotary file complete a full three hundred and sixty degree rotation and come back to its original position. Due to the increased risk in file separations with these rotational NiTi rotary files, reciprocating rotary files were presented as they were thought to put less force on the file itself.

Figure 1: Rotating rotary file vs reciprocating file kinematics

According to the American Association of Endodontics, over fifteen million root canal treatments are done every year. From this total, 75% of all nonsurgical endodontic procedures are done by general dentists while only 25% are done by endodontists. It is also estimated that endodontists only complete 62% of the molar endodontic treatments. With this large percentage of root canal treatments done by general dentists, it emphasizes the importance of properly training dental students during their predoctoral

endodontic education in dental school. Currently, in dental curricula throughout the United States, there is no standardization on how and which rotary file systems are taught to dental students in their endodontic preclinical courses. So that brings up the question, is there a rotary file system that dental schools should start dental students with when beginning their endodontic education?

The majority of research studies currently published on examining the quality of root canal instrumentation and shaping of preparations are done by practicing clinicians or post graduate residents. There are currently no studies that could be found on looking at the use of rotational and reciprocating file systems on the quality of their root canal preparations specifically by the use of novice dental students. In general, there are very few studies looking at the use of endodontic rotary files by dental students. This may due to the difficulty in conducting research studies at specific times in a dental school curriculum. This is an important research area which can help enlighten educators on whether it is beneficial to teach novice dental students endodontic instrumentation with a specific rotary file system when beginning their endodontic education. This study looks to provide more knowledge to this educational aspect of endodontics. This study aims to examine the influence of kinematics of nickel-titanium instruments (reciprocation vs rotation) on the shaping ability, canal transportation and centering ratio, of novice pre-doctoral sophomore dental students and their preference after its use.

CHAPTER 2
MATERIALS AND METHODS

Twenty one pre-doctoral second year dental students (D2) were recruited in this study using a random number generator and at the Temple University Kornberg School of Dentistry. None of the students had any clinical or endodontic experience prior to participating in this study. All of the students had just successfully completed their preclinical endodontics lab course, and had no prior experience with NiTi rotary instrumentation. No student had any experience using ProTaper Gold and WaveOne Gold used in this study.

Prior to beginning the study, each student was given an introduction on the fundamentals to each of the rotary file systems. This introduction was given using the manufacturer's guidelines of each rotary file system so that each student understood how to utilize them properly. Each of the students were given two identical pre-accessed mandibular left molar 3-dimensional printed replicas (TrueTeeth; PlanBDental). Each tooth was pre-marked on its mesiobuccal (MB) and mesiolingual (ML) cusp tips in order to ensure each student was using the same reference points when completing instrumentation. Both of the mesiobuccal and mesiolingual canals in each of the 3D printed replicas were hand instrumented to a size #15K file by a single endodontic resident prior to the students receiving them. This was to ensure that a glide path preparation was made prior to rotary instrumentation. The working length was determined using a stainless steel #15K file. The #15K file was brought through the canal, through a microscope, and visualized at the apical foramen and brought back 0.5mm in order to obtain the working length. The proper determined working lengths,

17.5mm for both the mesiobuccal and mesiolingual canals, were given to each student prior to instrumentation. Each student also received set of ProTaper Gold rotary files (Sx, S1, S2, F1 and F2) and a WaveOne Gold Primary reciprocating file. The teeth were divided up into two groups for each rotary file system being used: ProTaper Gold (PTG) (n=21) and WaveOne Gold (WOG) (n=21). Each student instrumented both the mesiobuccal and mesiolingual canals using each file system and irrigated with 5mL of saline water. The ProTaper Gold group was instrumented up to a size F2 by all students. The file system which the students began with was also determined using a random number generator. This was to minimize the influence of gaining experience with one file system prior to beginning the next system. The total instrumentation time for both the mesiobuccal and mesiolingual canals was recorded for each tooth. A questionnaire was completed after instrumentation regarding students' perception with a 5-point Likert scale: ease of use, flexibility, cutting efficiency, screwing effect and overall impression.

Image Analysis

Micro-computed tomography scanning was done prior to and after rotary instrumentation was completed using a SkyScan micro-CT machine. All teeth were placed into a premade polyvinyl siloxane (PVS) stent held by a borosilicate glass tube during the scanning process. This was to ensure all teeth were scanned in the exact same orientation. Initial scans were taken at a resolution of 20 micrometers by using the following settings: 124 mA, 75kV, 0.5mm aluminum filter, 6-frame averaging, and a rotation step of 0.5. All post-instrumentation scans were also taken using the same settings. After scans were completed, the data was reconstructed using the computer software NRecon (SkyScan) in order to be ready for data analysis.

Nickel Titanium Rotary Instrumentation Feedback Questionnaire

Please rate the performance of the **ProTaper Gold** rotary files on the following:

	Poor		Neutral		Excellent
Ease of Use	1	2	3	4	5
Flexibility	1	2	3	4	5
Cutting Efficiency	1	2	3	4	5
Screwing Effect	1	2	3	4	5
Overall Impression	1	2	3	4	5

Did Any File Separations Occur? Yes No
If so, circle which file(s) separated? Sx (Gold) S1 (Purple) S2 (White) F1 (Yellow) F2 (Red)

Total time spent during instrumentation using the ProTaper Gold Files on the mesial canals:

_____Minutes _____ Seconds

Please rate the performance of the **WaveOne Gold** rotary files on the following:

	Poor		Neutral		Excellent
Ease of Use	1	2	3	4	5
Flexibility	1	2	3	4	5
Cutting Efficiency	1	2	3	4	5
Screwing Effect	1	2	3	4	5
Overall Impression	1	2	3	4	5

Did Any File Separations Occur? Yes No

Total time spent during instrumentation using the WaveOne Gold Primary File on the mesial canals:

_____Minutes _____ Seconds

Which Rotary File System do you prefer:

ProTaper Gold WaveOne Gold

Figure 2: Questionnaire given to each student during the study

Calculating Canal Transportation and Centering Ratios

All reconstructions were analyzed using the computer software CTAn (SkyScan) to obtain the proper measurements in calculating the canal transportation and centering ratios. All of the 3D reconstructions were properly oriented and aligned prior to any measurements were taken. Measurements were calculated at 2mm, 5mm, and 8mm levels from the root apex to represent the apical, middle and coronal thirds of the root canal system respectively. All data was recorded using a Microsoft Excel spreadsheet. The method for calculating the canal transportation and centering ratios used was previously described by Gambill et al. The shortest distances from the completed instrumentations to the mesial or distal walls of the root are calculated at each of the three different cross sections where measurements were taken. These measurements were compared to those taken from the pre-instrumented scans. The canal transportation for both of the mesial canals were calculated using the following equations using Figure 4:

Canal transportation for mesiolingual canal **= (M1 - M2) – (D1 – D2)**

Canal transportation for mesiobuccal canal **= (M3 – M4) – (D3 – D4)**

Centering ratio for mesiolingual canal = **(M1 - M2) / (D1 – D2)** if **D1 – D2 > M1 - M2**

or **(D1 - D2) / (M1 – M2)** if **M1 – M2 > D1 - D2**

Centering ratio for mesiobuccal canal = **(M3 – M4) / (D3 – D4)** if **D3 – D4 > M3 – M4**

or **(D3 – D4) / (M3 – M4)** if **M3 – M4 > D3 – D4**

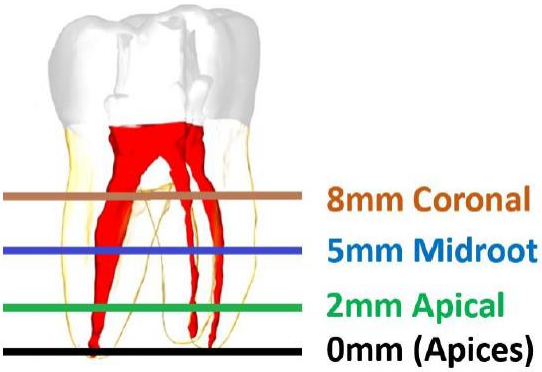
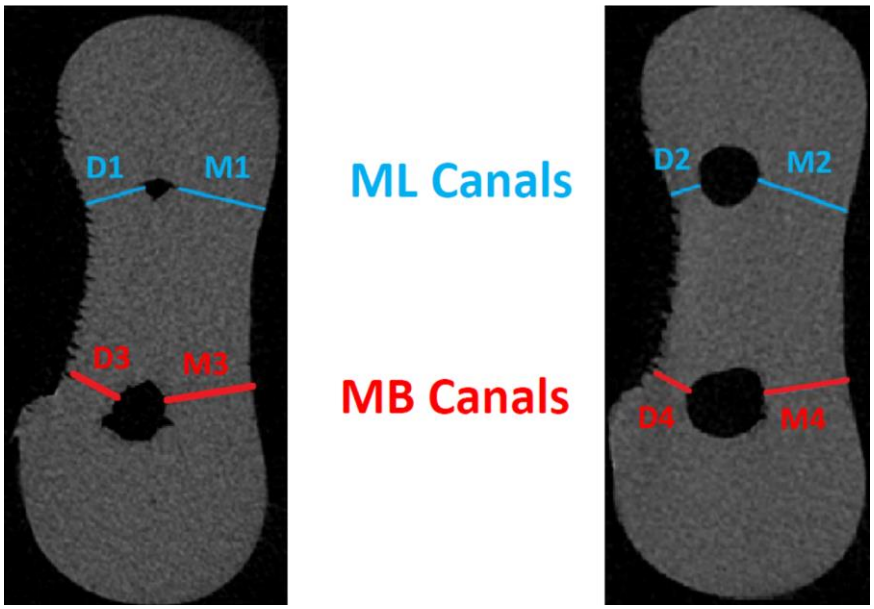


Figure 3: Illustration of the three different levels analyzed



Pre-instrumentation Post-instrumentation

Figure 4: Cone-beam computed tomography images at the coronal level from before and after instrumentation with the corresponding measurements for canal transportation and centering ratios

M1, M3, D1 and D3 all represent the shortest distances from the periphery of the uninstrumented canal to the mesial and distal surfaces of the root. M2, M4, D2 and D4 all represent the shortest distances from the periphery of the instrumented canal to the mesial

and distal surfaces of the root. When looking at canal transportation, a result of 0 indicates that no transportation occurred and that the instrumentation followed the original root canal anatomy. A result greater than 0 indicates that transportation has occurred towards the mesial direction, whereas a result less than 0 indicates that transportation occurred towards the distal direction. Centering ratio measures the ability of the instrumentation to stay centered within the canal. In the centering ratio calculations, if (D3 – D4) differs from (M3 – M4) for the mesiobuccal canals, then the denominator is the larger value between (D3 – D4) and (M3 – M4) while the numerator is the smaller value. This was calculated the same way when looking at the values for (M1 - M2) and (D1 – D2) in the mesiolingual canals. A centering ratio result of 1 means that the instrumentation had perfect centering, and a value closer to 0 means that the instrumentation was less centered.

Statistical Analysis

The software program Stata Version 17.0 was used for statistical analysis. The results for the canal transportation and centering ratios were statistically analyzed using a paired t-test to compare the groups. The results from the questionnaire were statistically analyzed using a Pearson chi-square test. The statistical significance level was set at $p < .05$.

CHAPTER 3
RESULTS

Canal Transportation and Centering Ratio

The results for the means and the standard deviations of the canal transportations and centering ratios for all three cross sections (coronal, middle, apical) are shown in Tables 1 and 2 respectively.

Canal	Level	Mean ± standard deviation (mm)	
		WaveOne Gold	ProTaper Gold
ML	Coronal	0.361 (±0.052)	0.340 (±0.125)
	Middle	0.154 (±0.110)*	0.311 (±0.129)
	Apical	0.045 (±0.035)*	0.158 (±0.086)
MB	Coronal	0.081 (±0.071)	0.084 (±0.054)
	Middle	0.143 (±0.093)*	0.210 (±0.126)
	Apical	0.089 (±0.037)	0.126 (±0.091)

* $p<0.05$

Table 1 – Statistical analysis for the mean canal transportation between groups

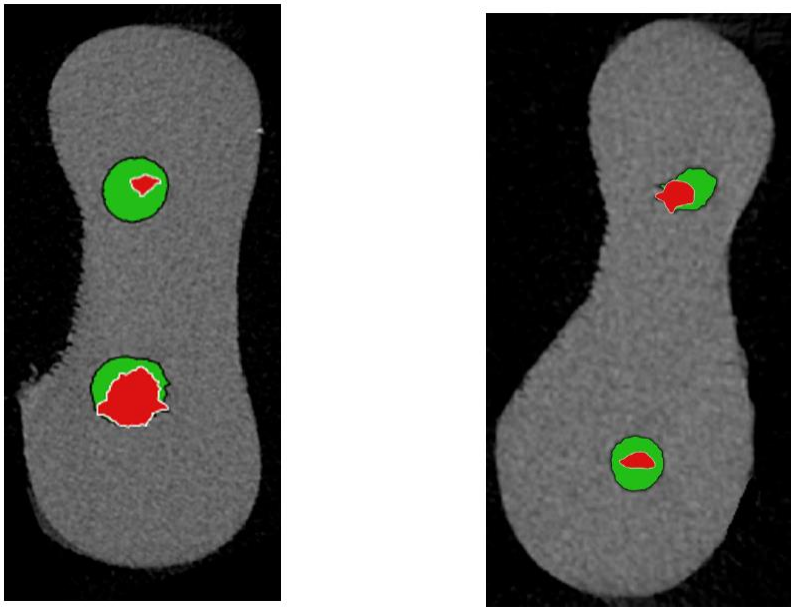
Canal	Level	Mean ± standard deviation	
		WaveOne Gold	ProTaper Gold
ML	Coronal	0.135(±0.073)	0.249(±0.138)*
	Middle	0.476(±0.211)*	0.224(±0.119)
	Apical	0.356 (±0.253)*	0.185(±0.166)
MB	Coronal	0.693(±0.221)	0.606(±0.203)
	Middle	0.363(±0.311)	0.328(±0.184)
	Apical	0.193 (±0.237)	0.381 (±0.334)

* $p<0.05$

Table 2 – Statistical analysis for the mean centering ratios between groups

Looking at the canal transportation results in the mesiolingual canals, there was a statistically significant difference for both of the middle and apical level groups. Both the middle and apical groups demonstrated that the WaveOne Gold reciprocating system had significantly less transportation than the ProTaper Gold groups ($p < .05$). At the coronal level of the mesiolingual canal, there was no significant difference in the canal transportation between the two rotary file systems. For the mesiobuccal canal, the WaveOne Gold group had significantly lower canal transportation compared to the ProTaper Gold group in the middle third ($p < .05$, WOG: 0.143 ± 0.093 vs PTG: 0.210 ± 0.126). There were no statistically significant differences noted in the canal transportations between the two rotary file systems at both the apical and coronal levels in the mesiobuccal canals.

Additionally, in the mesiolingual canals there were statistically significant differences in the centering ratios between the two rotary file systems at all three levels ($p<.05$). At the coronal level, ProTaper Gold preparations were seen to be more centered than the WaveOne Gold preparations (WOG: 0.135 ± 0.073 vs PTG: 0.249 ± 0.138). One the other hand, at the middle and apical levels, WaveOne Gold preparations were seen to be significantly more centered than the ProTaper Gold preparations ($p < .05$, middle WOG: 0.476 ± 0.211 vs PTG: 0.224 ± 0.119, apical WOG: 0.356 ± 0.253 vs PTG: 0.185 ± 0.166). In the mesiobuccal canals, there were no statistically significant differences noted in the centering ratios between the two rotary file systems at the coronal, middle or apical levels analyzed.



(A) **(B)**

Figure 5: Micro CT images of samples from different levels (red: preinstrumented canal; green: post-instrumented canal with rotary file); (A) Coronal level using PTG; (B) Apical level using WOG

Every student completed the questionnaire after they finished their root canal preparations of both teeth. The results are shown in Table 3 for the Likert scale data between the two rotary file systems. There were three categories that displayed

	ProTaper Gold	WaveOne Gold
Ease of Use *	3.476 (±0.98)	4.760 (±0.625)
Flexibility	3.857 (±1.014)	4.333 (±0.730)
Cutting Efficiency	3.952 (±1.117)	4.476 (±0.680)
Screwing Effect *	3.048 (±1.431)	4.333 (±0.966)
Overall Impression *	3.714 (±1.146)	4.762 (±0.625)

* p<0.05

Table 3: Analysis of questionnaire Likert scale with means and standard deviations

statistically significant differences between WOG and PTG which were the ease of use, screwing effect, and the overall impression ($p < .05$). In the category of ease of use, students ranked WOG as being significantly easier to use than PTG ($p < .05$). In the category of screwing effect, WOG was ranked significantly higher than PTG by students ($p < .05$). In the category for overall impression, WOG was ranked significantly higher than PTG once again by the students ($p < .05$). WOG preparations also took significantly less time than preparations done with PTG by the students ($p < .05$, WOG: 218 sec vs PTG: 446.57 sec). 90.48% of the students preferred using WOG during their instrumentation while 10.52% of the students preferred using PTG.

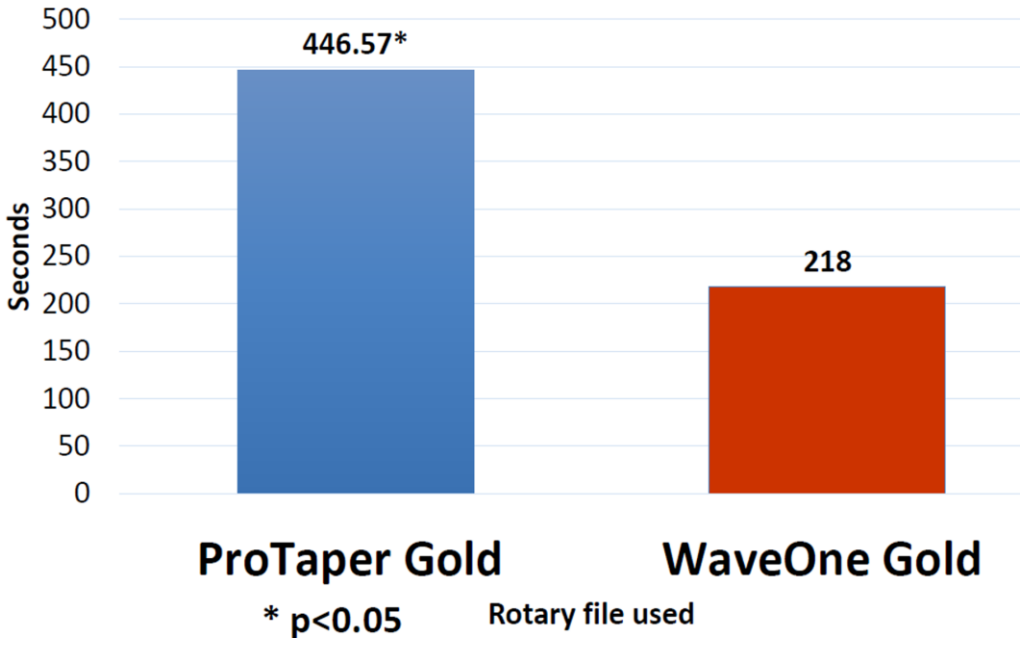


Figure 6: Average instrumentation times for WOG and PTG

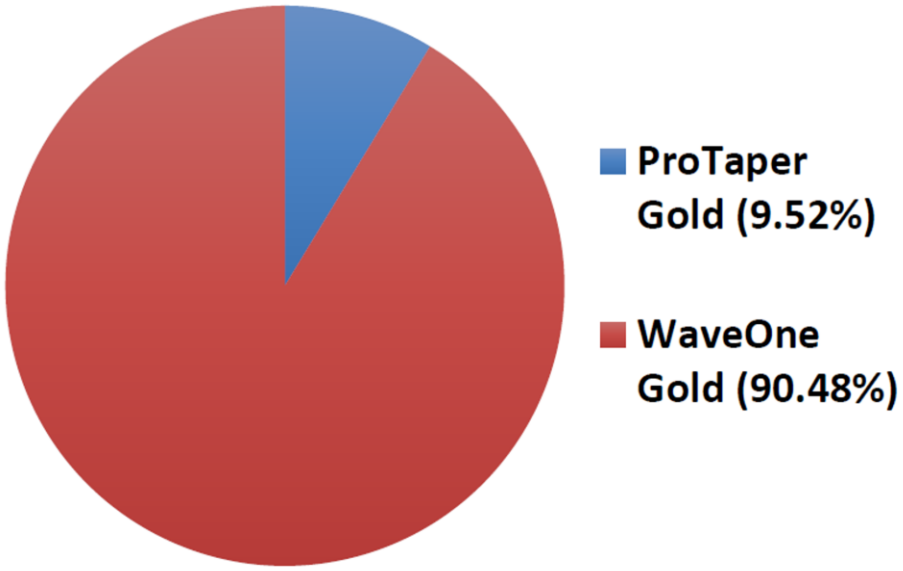


Figure 7: Student preference between WOG and PTG for instrumentation

CHAPTER 4
DISCUSSION

In this study, the mean canal transportation and centering ratio results of both the PTG and WOG rotary file systems were compared at the three levels: apical (2mm), middle (5mm) and coronal (8mm) from the anatomic apex of the teeth. Each of these levels were incorporated to depict the various locations within the canal where iatrogenic errors may occur. The results for the canal transportation in the ML and MB canals illustrate how the WOG had significantly less canal transportation than PTG at three separate levels: the middle and apical levels of the ML canal, and the apical level of the MB canal. At almost all of the other levels, with the exception of the coronal level of the ML canal, WOG still was seen to have less canal transportation than PTG, however the results were not statistically significant ($p<.05$). In respect to the centering ratios, the ML canal showed that WOG had significantly better centering in the middle and apical levels compared to PTG. Many previously published articles also show that reciprocating file systems have less transportation and more centered preparations than rotational file systems and attribute these differences may be due to the working motion and cross section design of the WOG compared to PTG.

On the other hand, it was found that PTG had significantly more centering in the coronal level of the ML canal which contradicted the other findings. A study done by Shi et al. also found that PTG showed significantly better centering ability than WOG at coronal curvatures specifically at 4,5, and 6mm from the apex ($p<.05$). This study used resin blocks with simulated S-shaped canals, and data was analyzed by superimposition of the pre and post images taken of the canals. This finding may be attributed to larger

diameter of the PTG file in the coronal level in relation to the WOG. Consistent with this study, Shi et al. also found that WOG was shown to have significantly less transportation and better centering at the apex of the resin blocks. With all of the different methodologies, such as type of teeth (extracted vs 3D-printed), used in comparable studies, there are differing outcomes between the shaping ability between WOG and PTG. Currently, to the best of our knowledge, there are no studies published which evaluate the canal transportation and centering ratio of root canal preparations completed by novice dental students, however there are studies where the root canal preparations are done by endodontists and endodontic residents.

A study done by Vyver et al. in 2019 also showed similar findings when looking at canal transportation done with WOG and the rotating file systems One Shape (OS) and ProTaper Next (PTN). This study had experienced clinicians instrument one hundred thirty-five extracted human maxillary molars. The results showed that the WOG group exhibited a significantly lower canal transportation than both rotational rotary files OS and PTN at each of the apical, middle and coronal levels ($p < .05$).

Kim et al. in 2021 also compared canal transportation of PTG and WOG in resin blocks and analyzed data using superimposed images of the root canal preparations before and after instrumentation. Their study found that the PTG group showed significantly more transportation than the WOG group at the 2mm and 3mm levels from the apex ($p<.05$). This was attributed to the increased apical taper present in PTG compared to WOG which are 0.08 and 0.07 respectively. This increased taper at the apical area leads to less flexibility and higher transportation in comparison to files of the same size. It was also found that the PTG group had longer preparations times compared

to the WOG group. This was attributed to the increased number of files present in the PTG system in comparison to the single file WOG system.

Furthermore, Singh et al in 2019 conducted a study which assessed the canal transportation and centering ratios using WOG, PTG and another NiTi rotating file system 2Shape (2S). This study used extracted mandibular molars and the data was analyzed using the pre and post instrumentation cone-beam computed tomography (CBCT) images at three levels: 3mm, 5mm and 7mm from the apex. The PTG group showed significantly more transportation and less centering than both the WOG and 2S groups at all three levels which were analyzed. These results are consistent with the canal transportation results from this study, but are in conflict with the centering ratio results for the coronal level of the ML canal in this current study.

The results from the questionnaire in this study are also supported by previous research studies. Kwak et al. in 2016 conducted a study examining the preference of undergraduate dental students after their first experience using nickel-titanium rotary files, specifically WaveOne (WO) and ProTaper Universal (PTU). The results of this study found that the students ranked WO significantly higher than PTU on the three categories of flexibility, screwing effect, and feeling-safety ($p<.05$). This result supports the current study as students also ranked WOG significantly higher than PTG on screwing effect, but also in ease of use and overall impression. Similarly to this study, instrumentation time with WO was significantly shorter than PTU. This result can again be attributed to the increased number of files used for PTU. However, 71% (55/77) of the students stated that they preferred using the WO system over the PTU system which only 29% (22/77) of the students preferred. This result differs from the current study where

approximately 90% of students preferred the WOG. This may be attributed to the small sample size of students used in this study.

Weaknesses of this study include that freshly extracted teeth were not used in this study. Even though the 3D-printed replicas used allowed for identical anatomy for each tooth being used, the structural properties of the resin differ in comparison to dentin. Also, another limitation of this study is the small sample size. By having more students participate in this study, each student would have instrumented one tooth in order to minimize any bias. Future studies are still needed in order to assess if there are further advantages to training novice dental students with reciprocating rotary systems when learning endodontics, but this study can serve as a framework to answer the question.

CHAPTER 5
CONCLUSIONS

This study aimed to examine the influence of kinematics of nickel-titanium instruments (reciprocation vs rotation) on the shaping ability, canal transportation and centering ratio, of novice pre-doctoral sophomore dental students and their preference after its use. Compared to a rotation NiTi file system, reciprocation NiTi file system was preferred by novice sophomore dental students, and it also showed less canal transportation and better centering ability with shorter instrumentation times. Limitations of this study include the use of artificial tooth replicas and small sample size. Future studies are still needed in order to assess if there are further advantages to training novice dental students with reciprocating rotary systems when learning endodontics, but this study can serve as a framework to answer the question.

REFERENCES CITED

Ahn SY, Kim HC, Kim E. Kinematic Effects of Nickel-Titanium Instruments with Reciprocating or Continuous Rotation Motion: A Systematic Review of In Vitro Studies. J Endod. 2016 Jul;42(7):1009-17.

Al Raisi H, Dummer PMH, Vianna ME. How is Endodontics taught? A survey to evaluate undergraduate endodontic teaching in dental schools within the United Kingdom. Int Endod J. 2019 Jul;52(7):1077-1085.

Cheung GS, Liu CS. A retrospective study of endodontic treatment outcome between nickel-titanium rotary and stainless steel hand filing techniques. J Endod. 2009 Jul;35(7):938-43.

Conceição I, Ferreira I, Braga AC, Pina-Vaz I. Simulated root canals preparation time, comparing ProTaper Next and WaveOne Gold systems, performed by an undergraduate student. J Clin Exp Dent. 2020 Aug 1;12(8):e730-e735.

Gambill JM, Alder M, del Rio CE. Comparison of nickel-titanium and stainless steel hand-file instrumentation using computed tomography. J Endod. 1996 Jul;22(7):369-75.

Gancedo-Caravia L, Bascones J, García-Barbero E, Arias A. Suitability of different tooth replicas for endodontic training: perceptions and detection of common errors in the performance of postgraduate students. Int Endod J. 2020 Apr;53(4):562-572.

Gergi R, Arbab-Chirani R, Osta N, Naaman A. Micro-computed tomographic evaluation of canal transportation instrumented by different kinematics rotary nickel-titanium instruments. J Endod. 2014 Aug;40(8):1223-7.

Hargreaves KM Berman LH. *Cohen's Pathways of the Pulp*. Eleventh ed. St. Louis Missouri: Elsevier; 2016.

Holmes S, Gibson R, Butler J, Pacheco R, Askar M, Paurazas S. Volumetric Evaluation of 5 Root Canal Obturation Methods in TrueTooth 3-dimensional-Printed Tooth Replicas Using Nano-computed Tomography. J Endod. 2021 Mar;47(3):485-491.e4.

Kabil E, Katić M, Anić I, Bago I. Micro-computed Evaluation of Canal Transportation and Centering Ability of 5 Rotary and Reciprocating Systems with Different Metallurgical Properties and Surface Treatments in Curved Root Canals. J Endod. 2021 Mar;47(3):477-484.

Kim, H., Jeon, SJ. & Seo, MS. Comparison of the canal transportation of ProTaper GOLD, WaveOne GOLD, and TruNatomy in simulated double-curved canals. *BMC Oral Health* **21**, 533 (2021). https://doi.org/10.1186/s12903-021-01854-z

Kwak SW, Cheung GS, Ha JH, Kim SK, Lee H, Kim HC. Preference of undergraduate students after first experience on nickel-titanium endodontic instruments. Restor Dent Endod. 2016 Aug;41(3):176-81.

Mahmoodi B, Azaripour A, Sagheb K, Sagheb K, Willershausen B, Weusmann J. Undergraduate Students' Acceptance of a Reciprocating One-File System for Endodontic Treatment. Eur J Dent. 2020 Jul;14(3):393-396.

Pettiette MT, Delano EO, Trope M. Evaluation of success rate of endodontic treatment performed by students with stainless-steel K-files and nickel-titanium hand files. J Endod. 2001 Feb;27(2):124-7.

Shi L, Zhou J, Wan J, Yang Y. Shaping ability of ProTaper Gold and WaveOne Gold nickel-titanium rotary instruments in simulated S-shaped root canals. J Dent Sci. 2022 Jan;17(1):430-437.

Singh S, Abdul MSM, Sharma U, Sainudeen S, Jain C, Kalliath JT. An *in vitro* Comparative Evaluation of Volume of Removed Dentin, Canal Transportation, and Centering Ratio of 2Shape, WaveOne Gold, and ProTaper Gold Files Using Cone-Beam Computed Tomography. J Int Soc Prev Community Dent. 2019 Sep 30;9(5):481-485.

Swathi UB, Ramesh S, Pradeep S, Comparative Evaluation of Canal Centering Ability of Three File Systems, Wave One, Wave One Gold and ProTaper Gold File Systems – An In Vitro Study, J Res Med Dent Sci, 2020, 8 (7): 447-453.

Van der Vyver PJ, Paleker F, Vorster M, de Wet FA. Root Canal Shaping Using Nickel Titanium, M-Wire, and Gold Wire: A Micro-computed Tomographic

Comparative Study of One Shape, ProTaper Next, and WaveOne Gold Instruments in Maxillary First Molars. J Endod. 2019 Jan;45(1):62-67.

Yamamura B, Cox TC, Heddaya B, Flake NM, Johnson JD, Paranjpe A. Comparing canal transportation and centering ability of endosequence and vortex rotary files by using micro-computed tomography. J Endod. 2012 Aug;38(8):1121-5.

Yılmaz F, Eren İ, Eren H, Badi MA, Ocak M, Çelik HH. Evaluation of the Amount of Root Canal Dentin Removed and Apical Transportation Occurrence after Instrumentation with ProTaper Next, OneShape, and EdgeFile Rotary Systems. J Endod. 2020 May;46(5):662-667.