Root Canal Shaping Using NiTi, M-wire and Gold-wire: A Micro-computed Tomographic Comparative Study of One-Shape, ProTaper Next and WaveOne Gold instruments in Maxillary First Molars

Peet J van der Vyver, BChD, MSc, PhD*, Farzana Paleker, BChD, MSc*,
Martin Vorster, BChD, MSc*, Francois A de Wet, BChD, MSc, DSc*

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

Corresponding author: Farzana Paleker
Email: farzanapaleker@gmail.com

Postal address: Oral and Dental Hospital, 4th and 5th Level, 31 Bophelo Road, Prinshof Campus, Riviera, Pretoria, 0002, South Africa

Research facility: The South African National Centre for Radiography and Tomography, Radiation Science, South African Nuclear Energy Corporation (Necsa), Pretoria, South Africa

Highlights

- This study compared canal shaping with the rotary One Shape (nickel titanium), rotary ProTaper NEXT (M-Wire), and reciprocating Primary WaveOne Gold (Gold wire) after glide path preparation with K-Files, One G, and ProGlider.
- No statistically significant difference in the mean centering ratios at the apical, midroot, and coronal levels of the various glide path groups in combination with the shaping instruments.
- WaveOne Gold exhibited the lowest transportation values at all levels with ProGlider.
- ProTaper NEXT exhibited the highest volume of dentin removed regardless of the glide path preparation technique used.

Abstract

Introduction: The aim of this study was to evaluate the root canal shaping effect of instruments manufactured from nickel-titanium, M-wire and Gold-wire with different glide path preparation techniques. **Methods:** One hundred and thirty-five mesiobuccal canals of extracted human maxillary molars were first randomly divided into three equal GPP groups (n=45) for glide path preparation with K-Flex files (K; Dentsply Sirona, Ballaigues, Switzerland), One-G (OG; Micro-Mega, Besançon, France) and ProGlider (PG; Dentsply Sirona). Specimens of each glide path group were further divided equally into 3 groups for instrumentation with ProTaper Next (PTN; Dentsply Sirona), One-Shape (OS; Micro-Mega) and WaveOne Gold (WOG; Dentsply Sirona) systems (n=15). Micro-CT was used to scan teeth before instrumentation and after shaping to compare centering ratio and canal transportation values at the apical, midroot, and coronal levels and the overall changes in canal volume. Data sets were statistically analysed (ANOVA and Kruskal-Wallis H tests) **Results:** CRs for all groups were statistically similar at all levels. Apical CT was significantly high for K/OS and K/PTN (P = .003). Midroot CT was significantly high for K/PTN, K/OS, and OG/OS (P = .0003). Coronal CT was significantly high for K/PTN and K/OS (P = .011). The highest change in canal volume was seen with all PTN groups and the lowest with PG/WOG (P = .06). **Conclusion:** WOG manufactured from Gold-wire, combined with PG, showed better root canal shaping ability, and removed less dentin from the canal walls. The nickel-titanium (OS) and M-wire (PTN) instruments used in combination with KF significantly transported more canals. PTN removed the most dentin from the canal walls regardless of the GPP technique.

Keywords: Glide path, rotation, reciprocation, centering ability, transportation, changes in canal volume, K-Files, One G, ProGlider, OneShape, ProTaper Next, WaveOne Gold

Introduction

Correct mechanical instrumentation of the root canal must result in a continuously tapered funnel-shaped canal that corresponds to the original canal anatomy. This is often difficult to achieve considering the complex internal morphology of curved root canals. Iatrogenic preparation errors of curved canals can result in apical canal transportation, uncentered preparations, ledge formation, or perforation (1).

Canal transportation is a sustained deviation from the original axis of the canal during root canal instrumentation. Apical canal transportation is the removal of canal wall structure on the outside curve in the apical half of the canal, due to the tendency of files to restore themselves to their original linear shape during canal preparation (2). The importance of maintaining preparations that are centered and correspond to the original canal anatomy has been demonstrated (3, 4).

Glide path preparation (GPP) allows for more effective and safer rotary shaping because it guarantees that the root canal diameter is sufficiently large to receive the first shaping instrument (5, 6). A number of studies have illustrated the many benefits of glide path formation, which include decreased canal aberrations and decreased risk of shaping file fracture (5, 6, 8). The ProGlider (Dentsply Sirona, Ballaigues, Switzerland) is a single mechanical glide path file manufactured using M-Wire. It has a square cross-section with a diameter of 0.16 mm at D0 and is progressively tapered from 2% to 8% over its length. The One-G instrument (Micro-Mega, Besançon, France) is a single glide path file system with a 3% taper, a diameter of 0.14 mm at D0 and three cutting edges situated on three different radii relative to the canal axis.

Root canal study modalities like micro-computed tomography (micro-CT) permits detailed and non-destructive two- and three-dimensional evaluation of root canal geometry (9–11). Accompanying accurate measurement software allows matching multi-dimensional data from specimens before and after glide path preparation and shaping (12).

OneShape (Micro-Mega) is a single-file nickel-titanium (NiTi) rotary shaping system made of a conventional austenite NiTi. It has a tip size of 25, a constant taper of 6%

and is characterized by different cross-sectional designs over the entire length of the working part (13). The ProTaper NEXT system (Denstply Sirona), manufactured from M-wire, consists of five instruments: X1 (17.04), X2 (25.06), X3 (30.07), X4 (40.06) and X5 (50.06), which are all characterized by a rotational phenomenon known as “precession” or “swagger” (14). According to the manufacturer, most canals can be prepared using only the first two files. The WaveOne Gold file system (Dentsply Sirona), manufactured from a heat treated gold metal alloy, Gold-wire, exhibits a unique alternating off-centered parallelogram-shaped cross-section design with two 85-degree cutting edges (15). The WaveOne Gold file, like its predecessor WaveOne (Dentsply Sirona), is used in a reciprocation motion and has a counter-clockwise engaging angle of 150° and a clockwise disengaging angle of 30°.

The broad aim of this ex-vivo study was to evaluate the root canal-shaping effect of instruments manufactured from NiTi, M-wire and Gold-wire, using different GPP techniques and micro-CT scanning in curved mesiobuccal root canals of extracted human first maxillary molars. The null hypothesis was that there would be no differences between the groups in canal transportation, centering ability and changes in canal volume after GPP and shaping of curved root canals.

Materials and Methods

Specimen Preparation

One hundred and thirty-five extracted maxillary first molars with curved mesiobuccal root canals presenting with one or two separate mesiobuccal canals were selected from a group of 160 pre-scanned teeth using a XTH 225 ST micro-focus X-ray computed tomography system (Nikon Metrology, Leuven, Belgium). The micro-CT system was used at settings of 100 kV, 100 Ma and an isotropic resolution of 22 µm. The roots of the teeth were coupled in a polystyrene platform (2.5 x 2.5. 2.5 cm) in which they were aligned perpendicular to the scanning beam. Only first mesiobuccal root canals with curvatures between 25° and 35° and radii of less than 10 mm were selected, as determined by the Schneider method (16). VGStudioMax visualization software (Volume Graphics GmbH, Heidelberg, Germany) was used to confirm these curvatures. After access cavity preparation, working length was determined by subtracting 0.5 mm from the length of the canal measured to the major apical terminus under 10 times magnification. The mesial canals were explored with a size 08 K-file and canals were negotiated to patency. The specimens were coded and randomly divided into three equal experimental groups (n=45) for glide path preparation.

Glide Path Preparation

Glide path preparation was performed by a single operator in strict accordance with the manufacturer's recommendations for each system. All the rotary glide path files were operated by a 16:1 gear reduction hand piece powered by the X.Smart Plus endodontic motor (Dentsply Sirona). RC Prep (Premier, Pennsylvania, US) was used as a lubricating agent and 3% sodium hypochlorite as canal irrigation.

K-File group (KF): In each of the 45 canals, an initial reproducible glide path was prepared using pre-curved size 0.10, 0.15 and 0.20 stainless steel K-files. **One G group (OG):** In each of the 45 canals, a pre-curved stainless steel size 0.10 K-file was negotiated to working length and One G was used to enlarge each canal. **ProGlider group (PG):** In each of the 45 canals a pre-curved stainless steel size 0.10 K-file was negotiated to working length and the ProGlider was then used to enlarge each canal.

Root Canal Shaping

The specimens of each glide path group were randomly assigned to three equal groups of 15 canals each for root canal shaping.

Each glide path specimen group was randomly assigned to three equal groups (n=15) resulting in nine glide path/shaping groups: KF/OS (K-File + OneShape); KF/PTN (K-File + ProTaper NEXT); KF/WOG (K-File + WaveOne Gold); OG/OS (One G + OneShape); OG/PTN (One G + ProTaper NEXT); OG/WOG (One G + WaveOne Gold); PG/OS (ProGlider + OneShape); PG/PTN (ProGlider + ProTaper NEXT); and PG/WOG (ProGlider + WaveOne Gold). After canal preparation with the shaping instruments, all the specimens were scanned again to generate a canal-shaping scan for each specimen.

The 3D images obtained before instrumentation and after GPP and canal preparation, were reconstructed and interpreted in VGStudioMax software. The polystyrene specimen holder ensured that the teeth could be placed in the same position before and after instrumentation. In addition, the pre- and post-preparation images were co-registered using automated image registration.

Image Analysis

The method described by Gambill, Alder and Del Rio was used to measure canal transportation and centering (17). Canal transportation and centering ratios were evaluated after shaping the root canals with the preparation instruments (Fig. 1).

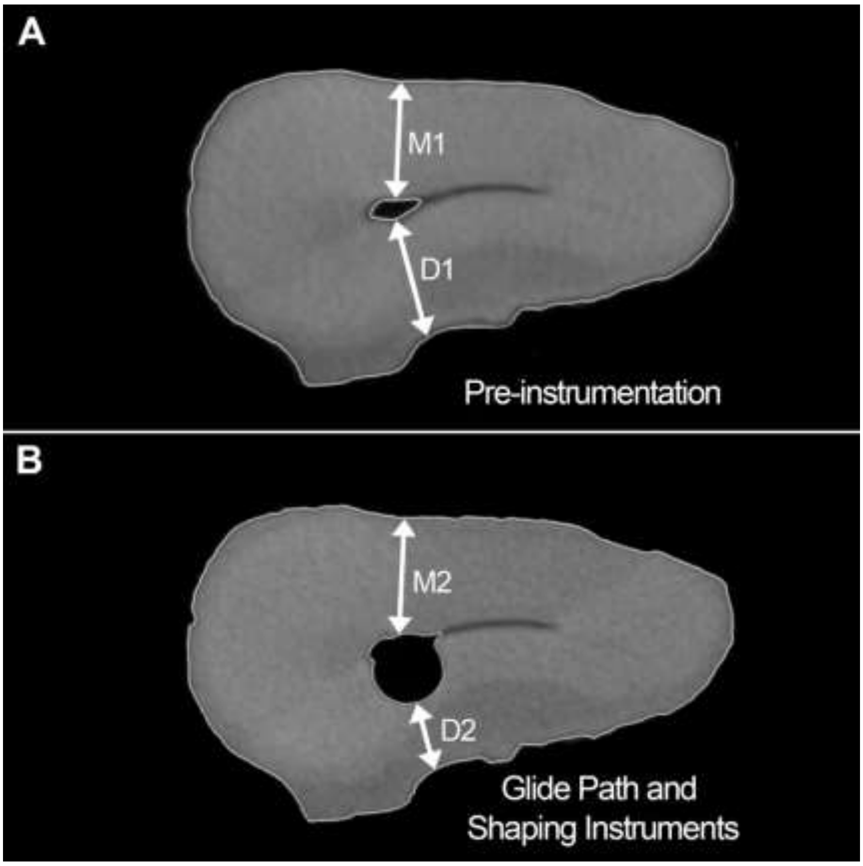

Figure 1. (*A*) Pre-instrumentation- and (*B*) post-canal-shaping CBCT images showing the effect of glide path and canal preparation and points of measurement for determining canal transportation and centering ratio.

The shortest distance from the prepared canal to the mesial or distal wall of the tooth at three different levels from the root apex was measured. Canal transportation and centering ratio values were measured at three different lengths from the anatomical apex of the mesiobuccal root canals. Cross-sections at levels 2 mm (apical), 5 mm (midroot) and 9 mm (coronal) were evaluated according to the equations set out immediately below (Fig. 2).

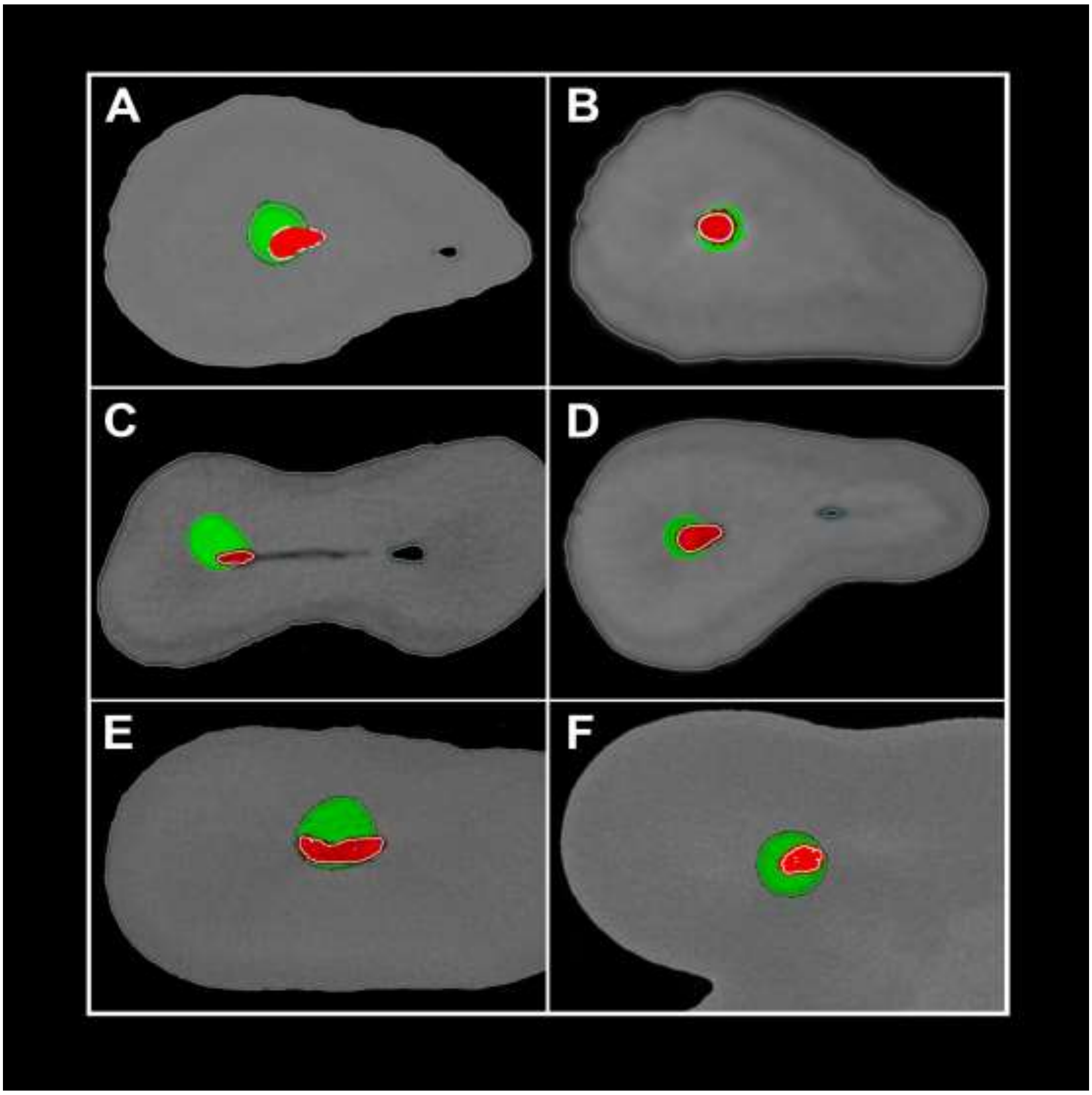

Figure 2. Representative samples from the different treatment groups that show canal transportation at the three levels (*red* – pre-instrumentation area; *green* – effect of canal preparation with shaping instrument): (*A*) Apical, KF/OS; (*B*) Apical, PG/WOG; (*C*) Midroot, KF/PTN; (*D*) Midroot, PG/WOG; (*E*) Coronal, K/PTN; (*F*) PG/WOG.

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

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

Where:

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

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

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

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

Canal transportation and centering ratios were evaluated after final preparation with the shaping instruments. All micro-CT measurements were calculated by a skilled third-party operator to avoid bias but were validated by an experienced clinician. Data was recorded on a Microsoft Excel (Microsoft Corp., Redmond, Washington) spreadsheet and verified. Before GPP and after canal instrumentation with the shaping instruments, the mesiobuccal canals of each specimen were traced and the total volume was measured. The volume of removed dentin in cubic millimeters was determined for each root canal by subtracting, first, the pre-instrumentation canal volume from the glide path volume and second, the pre-instrumentation canal volume from the canal instrumentation volume (18).

Statistical Analysis

A statistical analysis of the canal transportation and centering ratio values was performed by using one-way analysis of variance (ANOVA). Volume changes data showed a non-parametric distribution and the Kruskal-Wallis H test was used to compare amongst the groups. Statistical significance level was set at $P < .05$.

Results

Canal Transportation and Centering Ratio

Tables 1 and 2 show the mean and standard deviation values of the centering ability ratios and canal transportation at the three different levels for the different groups, respectively.

After shaping, the highest statistically significant apical canal transportation values were exhibited by KF/OS, followed by KF/PTN compared to the other groups ($P < .05$). The lowest apical canal transportation value was exhibited by PG/WOG, which was only statistically significantly lower than KF/OS, KF/PTN, and OG/PTN ($P < .05$).

At the midroot level, canal transportation was significantly higher for KF/PTN ($P < .05$) than all the other groups except KF/OS and OG/OS, which were statistically similar ($P > .05$). The PG/WOG showed the lowest apical canal transportation value but was only statistically significantly less than KF/OS, KF/PTN and OG/OS ($P < .05$).

Coronal canal transportation after canal shaping was statistically significantly highest for KF/PTN compared to all the other groups ($P < .05$), except for KF/OS. Again, lowest apical canal transportation value was exhibited by PG/WOG but was only statistically significantly lower than KF/OS and KF/PTN ($P < .05$).

No statistically significant difference was found in the mean centering ratios at the apical, midroot, and coronal levels of the various glide path groups in combination with the shaping instruments ($P > .05$).

TABLE 1. Statistical Analysis of Mean Centering Ratio Values for the Tested Groups

System	Apical		Midroot		Coronal	
	Mean ± SD	**Min–Max**	**Mean ± SD**	**Min–Max**	**Mean ± SD**	**Min–Max**
KF/OS	0.52 ± 0.36	0.058 – 1.276	0.49 ± 0.29	0.002 – 1.178	0.33 ± 0.27	0.096 – 1.166
KF/PTN	0.55 ± 0.41	0.068 – 1.543	0.45 ± 0.34	0.082 – 1.275	0.35 ± 0.34	0.025 – 1.443
KF/WOG	0.59 ± 0.35	0.033 – 1.421	0.43 ± 0.30	0.125 – 1.415	0.52 ± 0.33	0.156 – 1.418
OG/OS	0.53 ± 0.28	0.103 – 1.353	0.44 ± 0.25	0.76 – 1.043	0.35 ± 0.32	0.051 – 1.296
OG/PTN	0.56 ± 0.33	0.068 – 1.167	0.50 ± 0.39	0.004 – 1.377	0.37 ± 0.29	0.062 – 1.143
OG/WOG	0.60 ± 0.32	0.115 –1.376	0.45 ± 0.29	0.122 – 1,328	0.56 ± 0.16	0.301 – 0.855
PG/OS	0.55 ± 0.33	0.103 – 1.254	0.54 ± 0.35	0.002 – 1.271	0.34 ± 0.28	0.059 – 1.197
PG/PTN	0.60 ± 0.32	0.144 – 1.334	0.47 ± 0.29	0.43 – 1.223	0.44 ± 0.34	0.043 – 1.168
PG/WOG	0.62 ± 0.33	0.121 – 1.276	0.44 ± 0.29	0.136 – 1.279	0.58 ± 0.34	0.089 – 1.301
P value	.996		.998		.09	

TABLE 2. Statistical Analysis of Mean Transportation (mm) for the Tested Groups

System	Apical		Midroot		Coronal	
	Mean ± SD	**Min-Max**	**Mean ± SD**	**Min-Max**	**Mean ± SD**	**Min-Max**
KF/OS	0.107 [a] ± 0.046	0.035 – 0.219	0.118 [a] ± 0.036	0.036 – 0.174	0.167 [a] ± 0.037	0.084 – 0.259
KF/PTN	0.096 [b] ± 0.033	0.030 – 0.168	0.132 [b] ± 0.038	0.050 – 0.219	0.172 [b] ± 0.040	0.072 – 0.270
KF/WOG	0.078 ± 0.025	0.037 – 0.128	0.093 ± 0.021	0.053 – 0.128	0.148 ± 0.036	0.074 – 0.212
OG/OS	0.083 ± 0.020	0.054 – 0.128	0.113 [c] ± 0.027	0.060 – 0.162	0.158 ± 0.027	0.133 – 0.230
OG/PTN	0.085 [c] ± 0.026	0.035 – 0.136	0.107 ± 0.030	0.050 – 0.157	0.161 ± 0.032	0.127 – 0.250
OG/WOG	0.068 ± 0.026	0.022 – 1.126	0.093 ± 0.027	0.049 – 1.127	0.147 ± 0.029	0.130 – 0.203
PG/OS	0.081 ± 0.020	0.041 – 0.127	0.089 ± 0.023	0.052 – 0.151	0.154 ± 0.026	0.093 – 0.201
PG/PTN	0.084 ± 0.023	0.030 – 0.128	0.104 ± 0.033	0.23 – 0.171	0.151 ± 0.030	0.091 – 0.221
PG/WOG	0.065 [d] ± 0.026	0.040 – 0.136	0.086 [d] ± 0.020	0.054 – 0.120	0.140 [c] ± 0.027	0.072 – 0.202
P value	.003		.0003		.011	

Apical

[a] Statistically significantly different from KF/WOG, OG/OS, OG/PTN, OG/WOG, PG/OS, PG/PTN and PG/WOG

[b] Statistically significantly different from KF/WOG, OG/WOG and PG/WOG

[c] Statistically significantly different from PG/WOG

[d] Statistically significantly different from KF/OS, K/PTN and OG/PTN

Midroot

[a] Statistically significantly different from KF/WOG, OG/WOG, PG/OS and PG/WOG
[b] Statistically significantly different from KF/WOG, OG/PTN, OG/WOG, PG/OS, PG/PTN and PG/WOG
[c] Statistically significantly different from PG/OS and PG/WOG
[d] Statistically significantly different from KF/OS, KF/PTN and OG/OS

Coronal

[a] Statistically significantly different from PG/WOG
[b] Statistically significantly different from KF/WOG, OG/WOG and PG/WOG
[c] Statistically significantly different from KF/OS and KF/PTN

Volume of Removed Dentin

Table 3 depicts the mean and standard deviation values of the volume of removed dentin for each group after canal preparation. The three groups shaped with PTN exhibited the highest volume of dentin removed, with the highest displayed by the PG/PTN group. This was statistically significantly different from PG/WOG (P <. 05), which displayed the lowest mean volume of removed dentin.

TABLE 3. Descriptive Statistics: Changes in Canal Volume (in mm^3) with Shaping Instruments (n=15)

Shaping Method	Mean	Standard Deviation	Minimum Value	Maximum Value
KF/OS	3.034 [a]	0.903	2.053	5.629
KF/PTN	3.456 [b]	1.394	2.013	6.581
KF/WOG	3.078 [a]	0.567	1.882	3.822
OG/OS	3.211 [a]	1.263	1.672	5.346
OG/PTN	3.616 [b]	1.228	1.180	5.445
OG/WOG	3.025 [a]	1.097	1.453	5.342
PG/OS	2.875 [a]	0.772	1.692	4.274
PG/PTN	3.631 [b]	1.674	1.709	7.143
PG/WOG	2.646 [a]	1.518	1.027	5.755

Mean values with the same superscript letters were not statistically different at $P < .05$ using the Kruskal-Wallis H test.

Discussion

The mean canal transportation and centering ability values of the glide path and shaping instruments in this study were compared at levels 2 mm (apical), 5 mm (midroot), and 9 mm (coronal) from the anatomical apex of the tooth. These areas were chosen because they are particularly vulnerable to iatrogenic mishaps, especially in canals that are curved (17, 20). In the present study, no significant differences in the centering ability of the shaping groups were found in the apical, middle, and coronal thirds of the canals.

Canal transportation appears to have been influenced by GPP when OS and PTN were used after KF at the apical, midroot, and coronal levels. KF/OS and KF/PTN demonstrated significantly high transportation values at these levels. WOG displayed consistently low transportation values at all levels regardless of the glide path technique used. At the midroot level, PTN demonstrated significantly high transportation values irrespective of the glide path technique used. Midroot transportation results were also significantly high for OS, except when it was used after PG. At all levels, PG/WOG demonstrated the lowest transportation values. The significant difference between WOG groups and the two other shaping instruments can be explained by differences in working motion, cross-sectional design, and metallurgy. Adequate shaping ability of contemporary reciprocating files while preserving the original canal shape is a result of the interplay of three main factors: the reciprocation kinematics, the file cross-section, and the alloy type (21, 22).

The endodontic files included in this study have different cross-sections, diameters, tapers, alloy types, and tip designs and are used in either a rotary or reciprocating motion. The cross-section of OS represents three cutting edges, while the middle of the cross-sectional design progressively changes from a three-cutting-edge design to two cutting edges. This asymmetric cross section geometry of the file generates traveling waves of motion along the active part of the file that facilitates shaping without removal of excess amounts of dentin (22). PTN has an off-centered rectangular cross-sectional design that allows for removal of debris in a coronal direction allowing for more space around the flutes of the instrument and leading to improved cutting efficiency through continuous contact of the blades with the surrounding dentin walls (14). WOG instruments have an alternating off-centered parallelogram-shaped cross-sectional design with two 85-degree cutting edges design that limits engagement between the file and dentin to only one or two points of contact at any given cross section (Ruddle, 2016). The cross-sectional design of WOG, modified from the design of its predecessor, is said to increase flexibility (23).

It is worth noting that OS instruments are made of a conventional austenite 55-NiTi alloy and PTN instruments are made of M-wire alloy. The most important modification from WaveOne to WOG is the change from M-wire to Gold-wire (24). Gold-wire technology is based on heating the file and then slowly cooling it, whereas M-wire technology involves heat treatment before production. The manufacturer claims that the flexibility of files is improved by this new heat treatment method (25).

A recent study examined the centering ability and transportation of WOG after various GPP techniques and without any GPP. These researchers found no statistically significant difference in the mean combined centering ratios or transportation values after WOG was used following no GPP or any of the various GPP groups; they concluded that the Primary WaveOne Gold instrument was not influenced by the different glide path/no glide path techniques (26). A similar study using a single-file reciprocating system, Reciproc (VDW GmbH, Munich, Germany), also found no statistically significant difference between no glide path and various glide path groups in combination with this file (27). Various studies have shown that reciprocating file systems cause less transportation and maintain the original canal contour better than continuously rotating systems (28, 29). According to studies by Berutti et al. and Franco et al., this is particularly evident in the apical third where files used in a reciprocating motion exhibited more centralized preparations than those used in continuous rotation (29, 30). WaveOne and Reciproc instruments showed significantly less canal straightening and apical transportation than OS in a study by Saber, Nagy and Schäfer (31). These researchers attributed the results to the reciprocating motion of WaveOne and Reciproc, compared to the continuous rotation of OS.

In the present study, the final shaping size for all shaping systems was ISO 25 with taper sizes of 6% for OS, 6% for PTN, and 7% for WOG. In spite of the final taper size, transportation values and coronal centering ration were consistently favorable for WOG groups. The increased canal volume after GPP was statistically similar for the three groups. These findings are in keeping with those of another study that reported similar volume increases during glide path management with PathFiles and the PG instrument (32). The PG/WOG group showed the lowest mean volume of removed dentin and the PG/PTN group recorded the highest change in canal volume. High changes in canal volume were observed for all the PTN groups, most significantly after GPP with OG and PG. These results contrast with two other studies that demonstrated superior preservation of canal anatomy after using PTN (33, 34). The results of the current study could be attributed to the flexibility of the PTN M-wire alloy, its off-centered rectangular cross-section or the swaggering motion during instrument rotation (33, 35). This feature has been suspected of dramatically changing the instrument's envelope of motion, thereby increasing the final taper of the preparation. However this was disproved by Pasqualini et al., whose study concluded that PTN did not enlarge the canal more than the declared taper of instrument (33). In the present study, OS and WOG resulted in lower volumes of dentin removed. These results might be explained by differences in the design of the instruments or the brushing motion used with PTN during shaping.

Some authors consider both manual and rotary glide path techniques clinically reliable (20, 36). Bürklein and Schäfer reviewed various studies and concluded that the centering ratio and canal transportation effects of GPP with K-files are not significantly exacerbated by shaping (36). In the present study however, shaping outcomes were indeed affected by the GPP technique used. Results show significantly increased transportation at all levels when the rotary shaping systems were used after GPP with K-files. Similar results were found when the centering ratios were assessed at the coronal level. Results were, however, more favorable after reciprocation with WOG following any one of the three GPP techniques.

Within the limitations of the present study, the following can be concluded.

The reciprocating Primary WaveOne Gold instrument manufactured from Gold-wire, in combination with ProGlider, exhibited favorable root canal-shaping ability with regard to transportation and the volume of dentin removed during canal preparation. The rotary nickel-titanium (One Shape) and M-wire (ProTaper Next) instruments caused increased canal transportation after GPP with K-files. Shaping with ProTaper Next removed more dentin from the canal walls, regardless of the preceding GPP technique used.

Acknowledgements

The authors thank Dentsply Sirona for donating the files for this study and the South African National Centre for Radiography and Tomography, Radiation Science, South African Nuclear Energy Corp for the use of the Micro-Focus X-ray Tomography Facility, particularly Mr Jacobus Hoffman for his time and assistance with the reconstruction of micro-focus x-ray images. The authors also thank Prof H.S. Schoeman for his valuable support with statistical analysis. The authors deny any conflict of interest related to this study.

References

1 Hülsmann M, Peters OA, Dummer PMH. Mechanical preparation of root canals: shaping goals, techniques and means. Endod Top 2005;10:30–76.

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

3 Berutti E, Cantatore G, Castellucci A, et al. Use of nickel-titanium rotary PathFile to create the glide path: comparison with manual preflaring in simulated root canals. J Endod 2009;35:408–12.

4 Pasqualini D, Bianchi CC, Paolino DS, et al. Computed micro-tomographic evaluation of glide path with nickel-titanium rotary PathFile in maxillary first molars curved canals. J Endod 2012;38:389–93.

5 Berutti E, Negro AR, Lendini M, et al. Influence of manual preflaring and torque on the failure rate of ProTaper rotary instruments. J Endod 2004;30:228–30.

6 Varela-Patiño P, Martin-Biedma B, Liébana CR, et al. The influence of a manual glide path on the separation rate of NiTi rotary instruments. J Endod 2005;31:114–6.

7 Roland DD, Andelin WE, Browning DF, et al. The effect of preflaring on the rates of separation for 0.04 taper nickel titanium rotary instruments. J Endod 2002;28:543–5.

8 Nahmias Y, Cassim I, Glassman G. “ Own the canal ”– the importance of a

reproducible glide path. Oral Heal J 2013;(May):74–82.

9 Rhodes JS, Pitt Ford TR, Lynch JA. A comparison of two nickel-titanium instrumentation techniques in teeth using microcomputed tomography. Int Endod J 2000;33:279–85.

10 Paqué F, Ganahl D, Peters OA. Effects of root canal preparation on apical geometry assessed by micro-computed tomography. J Endod 2009;35:1056–9.

11 Peters OA, Paqué F. Root canal preparation of maxillary molars with the self-adjusting file: a micro-computed tomography study. J Endod 2011;37:53–7.

12 Peters OA, Peters CI, Schönenberger K, et al. ProTaper rotary root canal preparation: effects of canal anatomy on final shape analysed by micro CT. Int Endod J 2003;36:86–92.

13 Bürklein S, Benten S, Schäfer E. Shaping ability of different single-file systems in severely curved root canals of extracted teeth. Int Endod J 2013;46:590–7.

14 Van Der Vyver PJ, Scianamblo MJ. Clinical guidelines for the use of ProTaper Next instruments (Part I). Dent Trib 2014;7:12–6.

15 Webber J. Shaping canals with confidence : WaveOne GOLD single-file. Roots 2015;1:34–40.

16 Schneider SW. A comparison of canal preparations in straight and curved root canals. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1971;32:271–5.

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

18 Hashem AAR, Ghoneim AG, Lutfy RA, et al. Geometric analysis of root canals prepared by four rotary NiTi shaping systems. J Endod 2012;38:996–1000.

19 De-Oliveira Alves V, Da Silveira Bueno CE, Cunha RS, etal. Comparison among manual instruments and pathfile and mtwo rotary instruments to create a glide path in the root canal preparation of curved canals. J Endod 2012;38:117–20.

20 Xu X, Eng M, Zheng Y, etal. Comparative study of torsional and bending properties for six models of nickeltitanium root canal instruments with different cross-sections. J Endod 2006;32:372–5.

21 Park SY, Cheung GS, Yum J, et al. Dynamic torsional resistance of nickel-titanium rotary instruments. J Endod 2010;36:1200–4.

22 Capar ID, Ertas H, Ok E, et al. Comparative study of different novel nickel-titanium rotary systems for root canal preparation in severely curved root canals. J Endod 2014;40:852–6.

23 Özyürek T, Yilmaz K, Uslu G. Shaping ability of Reciproc, WaveOne GOLD, and HyFlex EDM single-file systems in simulated S-shaped canals. J Endod 2017;43:805–9.

24 Hieawy A, Haapasalo M, Zhou H, et al. Phase transformation behavior and resistance to bending and cyclic fatigue of protaper gold and protaper universal instruments. J Endod 2015;41:1134–8.

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

26 Vorster M, Van der Vyver PJ, Paleker F. Canal transportation and centering ability of WaveOne Gold in combination with and without different glide path techniques. J Endod 2018;44:1430-5.

27 De Carvalho GM, Sponchiado ESJ, Garrido ADB, et al. Apical transportation, centering ability, and cleaning effectiveness of reciprocating single-file system associated with different glide path techniques. J Endod 2015;41:2045–9.

28 Varela-Patiño P, Ibañez-Párraga A, Rivas-Mundiña B, et al. Alternating versus continuous rotation: a comparative study of the effect on instrument life. J Endod 2010;36:157–9.

29 Franco V, Fabiani C, Taschieri S, et al. Investigation on the shaping ability of nickel–titanium files when used with a reciprocating motion. J Endod 2011;37:1398–401.

30 Berutti E, Paolino DS, Chiandussi G, et al. Root canal anatomy preservation of

WaveOne reciprocating files with or without glide path. J Endod 2012;38:101–4.

31 Saber SE, Nagy MM, Schäfer E. Comparative evaluation of the shaping ability of WaveOne, Reciproc and OneShape single-file systems in severely curved root canals of extracted teeth. Int Endod J 2015;48:109–14.

32 Kirchhoff AL, Chu R, Mello I, et al. Glide path management with single- and multiple-instrument rotary systems in curved canals: A micro-computed tomographic study. J Endod 2015;41:1880–3.

33 Pasqualini D, Alovisi M, Cemenasco A, et al. Micro-computed tomography evaluation of ProTaper next and BioRace shaping outcomes in maxillary first molar curved canals. J Endod 2015;41:1706–10.

34 Gagliardi J, Versiani M, De Sousa-Neto MD, et al. Evaluation of the shaping characteristics of ProTaper Gold, ProTaper NEXT, and ProTaper Universal in curved canals. J Endod 2015;41:1718–24.

35 Elnaghy AM, Elsaka SE. Evaluation of root canal transportation, centering ratio, and remaining dentin thickness associated with Protaper NEXT instruments with and without glide path. J Endod 2014;40:2053–6.

36 Bürklein S, Schäfer E. Critical evaluation of root canal transportation by instrumentation. Endod Top 2013;29:110–24.