Assessment of mechanical properties of WaveOne Gold Primary reciprocating instruments

Tong FANGLI^{1,2}, Keiichiro MAKI², Shunsuke KIMURA², Miki NISHIJO², Daisuke TOKITA², Arata EBIHARA² and Takashi OKIJI²

¹Endodontic Department, Stomatological Hospital of Southern Medical University, Guangzhou, China

²Department of Pulp Biology and Endodontics, Division of Oral Health Sciences, Graduate School of Medical and Dental Science, Tokyo Medical and Dental University (TMDU), Tokyo, Japan

Corresponding author, Arata EBIHARA; E-mail: a.ebihara.endo@tmd.ac.jp

This study aimed to evaluate cyclic fatigue resistance and bending properties and torque/force generation of WaveOne Gold (WOG) Primary in comparison with WaveOne (WO) Primary and Reciproc (RE) R25. A cyclic fatigue test revealed that the WOG Primary took significantly longer time to fracture compared with the WO Primary ($p < 0.05$). The WOG Primary had the smallest load values at a deflection of 0.5 and 2 mm ($p < 0.05$), as measured with a cantilever bending test. Torque/force measurement demonstrated that maximum upward force and maximum counterclockwise torque values in the WOG Primary were significantly lower than those in the RE R25 ($p < 0.05$). Under the present experimental condition, the WOG Primary showed a higher cyclic fatigue resistance compared with the WO Primary, a higher flexibility compared with the WO Primary and RE R25, and generated a significantly lower maximum torque compared with the RE R25.

Keywords: Mechanical properties, WaveOne Primary, WaveOne Gold Primary, Reciproc R25

INTRODUCTION

Single-file root canal preparation with reciprocating nickel-titanium (NiTi) instruments aims to make the root canal preparation procedure easier, faster and safer compared with conventional multi-file rotary systems¹⁻³, and has gained popularity since the introduction of the Reciproc (RE; VDW, Munich, Germany) and WaveOne (WO; DentsplyMaillefer, Ballaigues, Switzerland) NiTi instruments. It has been reported that reciprocating motion reduces the risk of cyclic fatigue that is caused by tension and compression in proportion to that of rotational motion^{4,5}. However, single-file instruments are subjected to high stresses by shaping root canals with only one file. This occurs especially in the preparation of molar teeth with at least three root canals that can be complex, curved, and narrow. Therefore, it is critical for clinicians to be aware of the mechanical properties of different instruments and their effect on instrument performance to decrease the potential risk of fracture⁶.

WO Primary and RE R25 are two of the most commonly used files in the reciprocating system. Both are manufactured from M-wire with the same tip diameter and taper (size 25 tip and size 0.08 taper). The RE has an S-shaped cross section with 150° counterclockwise (CCW) and 30° clockwise (CW) movement during operation, whereas the WO features a modified convex triangular cross section in the apex that engages 170° CCW and 50° CW⁷ (Table 1).

Recently, the WaveOne Gold (WOG; Dentsply Maillefer) has been introduced to the market with the claim that metallurgical improvements in Gold-wire heat treatment increase the elasticity. Gold-wire heat treatment is a thermal cycling procedure that gives the

file a gold color by manual heating and then slow cooling, in contrast with the premanufacturing heat treatment of M-Wire technology⁸ (Table 1). The thermomechanical treatment that is applied to the Gold-wire may increase the flexibility and the cyclic fatigue resistance. ProTaper Gold (Dentsply Maillefer) is shown to be more flexible and resistant to cyclic fatigue than the ProTaper Universal (Dentsply Maillefer), which is attributed to this special gold heat treatment⁹.

Several articles have reported the cyclic fatigue resistance of the WOG instruments^{3,10}. The cyclic fatigue resistance of the WOG instruments has been shown higher than that of the WO instruments of corresponding sizes¹⁰. Moreover, WOG Primary instrument is reported to show a greater cyclic fatigue resistance compared with the WO Primary and RE R25³.

No previous study has combined the cyclic fatigue resistance, flexibility, and torque/force generation to evaluate the mechanical properties of the WOG. In this study, we aimed to evaluate these mechanical properties of the WOG Primary in comparison with the WO Primary and RE R25. The null hypothesis tested was that the cyclic fatigue resistance, flexibility, and torque/force generation of the WOG Primary are not different from those of the WO Primary and RE R25.

MATERIALS AND METHODS

Ninety reciprocating instruments, including 30 WOG Primary, 30 WO Primary, and 30 RE R25 with the same length of 25 mm were divided randomly into 3 groups ($n=10$ each) for cyclic fatigue testing, cantilever bending testing, and torque/force analysis.

Table 1 Specifications of NiTi instruments tested in this study

Instrument (Group)	Size	Taper at the tip (%)	Cross section	NiTi alloy
WaveOne Gold Primary (WOG)	#25	7	parallelogram	Gold-wire
WaveOne Primary (WO)	#25	8	convex triangular	M-wire
Reciproc R25 (RE)	#25	8	S-shaped	M-wire

Cyclic fatigue test

A custom-made three-pin device with a 38° curvature and 5-mm radius according to the criteria established in a previous study¹¹⁾ was used for cyclic loading. The specimen was connected with an endodontic motor (X-SMART Plus, Dentsply Maillefer), with the “WaveOne All” mode used for WO and WOG Primary, and the “Reciproc All” mode used for RE R25. The three pins were adjusted horizontally and fixed to bend 2 mm from the tip of the file. A load cell (LUR-A-50NSA1, Kyowa Electronic Instruments, Tokyo, Japan) fixed at the middle pins was used to detect the load during rotation and the output was connected to a personal computer (Vaio VGF-FE, Sony, Tokyo, Japan). All measurements were performed at 37°C. Friction and heat generation was reduced by using silicone oil (KF-96-100CS, Shin-Etsu Chemical, Tokyo, Japan).

The time to fracture (in seconds) was calculated by using data recorded with a computer. The fracture length was measured with a digital caliper (Digimatic CD-15CPX, Mitutoyo, Kanagawa, Japan) in millimeters.

Three fractured instruments that were selected randomly from each group were examined under a scanning electron microscope (Hitachi High-Tech S-3400, Tokyo, Japan) at an accelerating voltage of 15 kV, and photomicrographs of the fractured surfaces were observed at low and high magnifications.

Cantilever bending test

A universal testing machine (Autograph AG-IS, Shimadzu, Kyoto, Japan) was used to apply and record the load as described in previous studies¹¹⁾. The file was mounted on a movable stage and clamped 7.0 mm from the tip, and the loading point was set to 2.0 mm from the tip. The instrument was loaded (1.0 mm/min) until it achieved a 3-mm maximum deflection, and then unloaded. The bending loads were measured at deflections of 0.5 and 2.0 mm during the loading process, which corresponded to the elastic and super-elastic range, respectively. The temperature during the test was maintained at 37°C.

Torque/force analysis

A simulated straight canal in resin blocks (END3L001, Nissin Dental Products, Kyoto, Japan; 0.2 mm apical foramen diameter, 0.017 taper, and 14-mm length) was negotiated for a patency with a #10 stainless steel K-file (Zipperer, Munich, Germany) followed by a glide path preparation with a #15 stainless steel K-file in group RE R25, or a rotary instrument (ProGlider, Dentsply

Maillefer, #16 and 0.02 taper) in groups WOG and WO Primary, according to the manufacturer instructions. An automated root-canal instrument and torque/force analyzing device, which has been described elsewhere¹²⁾, was used to prepare canals. The handpiece of the X-SMART Plus motor was set to rotate in “WaveOne All” mode for WO and WOG Primary, and “Reciproc All” mode for RE R25. RC-Prep (Premier, Plymouth Meeting, PA, USA) was filled in the root canal as a lubricant during instrumentation, and the handpiece was programmed to move in a simulated pecking motion, that is downwards for 2 s and upwards for 1 s with a constant speed of 10 mm/min.

The torque and apical force generated in the blocks during preparation were detected through a torque/force measuring unit which was connected to a personal computer (Vaio VGF-FE, Sony), as described previously¹²⁾. The maximum torque and apical force values were recorded and compared.

Statistical analysis

The data were analyzed using Kruskal-Wallis test and Mann-Whitney *U* test with Bonferroni correction. SPSS 22.0 software (IBM-SPSS, Chicago, IL, USA) was used and the statistical significance level was set at $\alpha=0.05$.

RESULTS

In the cyclic test, the WOG Primary and RE R25 took significantly longer time to fracture compared with the WO Primary ($p<0.05$, one-way ANOVA and Tukey test, Table 2), whereas no statistical difference existed between WOG Primary and RE R25 ($p>0.05$, Table 1). RE R25 showed a longer fractured length than WOG Primary and WO Primary ($p<0.05$, Table 2). Photomicrographs from scanning electron microscopy showed typical features of cyclic fatigue failure, including crack initiation and propagation in the fractured area periphery, where striations were observed (Fig. 1).

In the bending test, the WOG Primary showed the smallest load values among all groups at a deflection of 0.5 mm ($p<0.05$, Kruskal-Wallis test and Mann-Whitney *U* Test, Table 3), whereas no difference existed between WO Primary and RE R25 ($p>0.05$, Table 3). At a deflection of 2 mm, the WOG Primary showed the smallest value, followed by RE R25 and WO Primary ($p<0.05$, Table 3).

In the torque/force analysis, the maximum upward apical force values and maximum CCW torque values in RE R25 were significantly higher than those in the WOG Primary and WO Primary ($p<0.05$, Kruskal-Wallis

Table 2 Time to fracture and length of fractured fragments of instruments subjected to cyclic fatigue test

Group	Time (s)	Length (mm)
WOG	236.11±18.25 ^a	6.20±0.24 ^c
WO	107.20±33.59 ^b	5.78±1.80 ^c
RE	274.22±66.63 ^a	7.26±0.18 ^d

Values are mean±standard deviation.

n=10 in each group.

Mean values with different superscript letters in a column are significantly different (*p*<0.05).

Fig. 1 Representative scanning electron microscopic images of the fractured surface of WOG Primary (a, b), WO Primary (c, d), and RE R25 (e, f) at low (left) and high (right) magnifications. The white arrows show fatigue striations that are typical of cyclic fatigue.

Table 3 Load values of cantilever bending test at a deflection of 0.5 and 2 mm

Group	Load (N)	
	0.5 mm	2 mm
WOG	0.34±0.19 ^a	2.09±0.26 ^e
WO	1.26±0.16 ^b	4.48±0.36 ^d
RE	1.10±0.15 ^b	4.00±0.55 ^e

Values are mean±standard deviation.

n=10 in each group.

Mean values with different superscript letters in a column are significantly different (*p*<0.05).

Table 4 Maximum apical force and maximum torque values in two directions

Group	Apical force (N)		Torque (N·m)	
	Upward	Downward	Counter-clockwise	Clockwise
WOG	-3.56±0.53 ^a	2.51±0.94 ^c	-12.95±2.52 ^d	3.64±1.33 ^f
WO	-3.39±0.49 ^a	2.41±1.85 ^c	-11.87±3.10 ^d	6.63±2.61 ^g
RE	-7.26±1.49 ^b	1.86±0.77 ^c	-25.86±3.14 ^e	9.54±3.64 ^g

Values are mean±standard deviation.

n=10 in each group.

Mean values with different superscript letters in a column are significantly different (*p*<0.05).

test and Mann-Whitney *U* Test, Table 4), whereas no difference was detected between the WOG Primary and WO Primary. The maximum CW torque for the WOG Primary was significantly smaller than that for the WO Primary and RE R25 (*p*<0.05, Table 4).

DISCUSSION

Despite many advantages of NiTi rotary instruments, fracture during root-canal preparation remains a major concern to clinicians, because it usually occurs without visible signs of metal deformation⁷. To improve the mechanical properties of the NiTi rotary instruments, many methods, including altering the metallurgy, design, and kinematics of the instruments, and heat treatments have been applied¹⁰. Two reciprocation NiTi systems, WO primary and RE R25 files were introduced into the market which has been reported that the reciprocating motion improved the fracture resistance during preparation by relieving the cyclic fatigue caused by tension and compression^{5,13}. Both WO Primary and RE R25 files are made of M-wire NiTi alloy. WOG files are the updated version of WO and manufactured from Gold-wire. M-Wire technology is based on heat treatment before production, while Gold-wire technology is performed by heating and then slowly cooling the file after production. Only a few experimental studies have examined the mechanical properties of the WOG. In this study, we intended to examine the mechanical characteristics of the WOG in terms of its cyclic fatigue resistance, flexibility, and torque/force generation. We

found that the WOG Primary showed a significantly longer time to fracture than the WO Primary, smaller bending load values than the WO Primary and RE R25, and a lower maximum upward apical force and maximum CCW torque compared with the RE R25. Thus, the null hypothesis was rejected.

The results of this study demonstrated that the WOG Primary took a longer time to fracture compared with the WO Primary. These results agree with earlier studies, which show that the cyclic fatigue resistance of the WOG is higher than that of the WO^{3,7,10,14}. The design, heat treatment, cross-sectional shape, and dimensions of endodontic instruments can have a significant influence on their performance and cyclic fatigue resistance^{15,16}. The WOG uses the same motion and kinematics as the WO, whereas the taper is decreased to 7%. It is well accepted that the cyclic fatigue resistance decreases with an increase in the file diameter¹⁷. A smaller WOG taper with a decreased instrument metal mass may account for an increased cyclic fatigue resistance compared with the WO. The WOG cross section is modified from that of a convex triangular WO shape to a parallelogram, with two cutting edges and an alternate one-point contact. Although there is no consensus on the effect of instrument cross-sectional shape on its cyclic fatigue resistance¹⁸⁻²⁰, this alternate one-point contact design decreases the number of contact points between the file and the dentin wall of the root canal, which may lead to a smaller stress on the WOG and a resultant higher cyclic resistance of the WOG compared with the WO. Furthermore, the WOG is made from Gold-wire, which

results from postmanufacture heat treatment, whereas the WO is made from M-wire with a premanufacture heat process¹⁰. This postmanufacture heat treatment may account for the higher cyclic fatigue resistance of the WOG than that of the WO.

However, the WOG Primary showed no difference with RE R25 in the cyclic fatigue resistance, which agrees with a previous study²¹. This may result because of the different rotational speed and reciprocating angle of the WOG and RE. According to the manufacturer, the “WaveOne All” mode for the WOG has a higher speed of 350 r/min compared with the 300 r/min of the “Reciproc All” mode. Also, the reciprocating angle of the “WaveOne All” mode is 170° CCW and then 50° CW, whereas the angle of the “Reciproc All” mode is 150° CCW and then 30° CW. The higher rotation speed and the larger reciprocating angle of the WOG could account for the cyclic fatigue generation to the level comparable with that of the RE. The WO showed a lower cyclic fatigue resistance compared with the RE, which agrees with most studies^{13,14,22,23}. However, previous studies have shown that the WOG has a higher cyclic fatigue resistance than the RE^{3,14}. The difference may arise because different cyclic models with different curvatures and radii were used. In our study, a custom-made three-pin device with a 38° curvature and a 5-mm radius was used to facilitate comparison with our previous results¹¹. In addition, RE showed a longer fractured length than WOG and WO, which may be attributable to the nearly vertical pitch angle and the longest pith length of RE.

Flexibility is an important property of the NiTi endodontic instruments because it anticipates the mechanical performance of the endodontic instruments whilst preparing curved canals²⁴. This study demonstrated that the WOG Primary exhibited a significantly smaller bending load than the WO Primary and RE R25, which agrees with previous studies^{8,14}. The flexibility is related closely to the transformation behavior, and it has been accepted that the thermomechanical treatment of NiTi alloys influences their transformation behavior strongly⁹. Superelasticity is caused by stress-induced martensitic transformation, which is a nonlinear recoverable behavior of NiTi shape memory alloys at temperatures above the austenite transformation finishing (Af) temperature¹⁴. Heat treatment of the WOG may improve the flexibility of the file by modifying the Af temperature¹⁰. A two-stage austenite to R-phase to martensite transformation often occurs after additional heat treatment, and the presence of an R phase indicates a better superelasticity of the NiTi instruments compared with a one-stage austenite to martensite transformation^{10,14}. The WOG uses a post-manufacture treatment by instrument heating and then slow cooling. Slow cooling after the annealing of nickel-rich alloys allows for precipitates of the Ni₄Ti₃ type to form, which increases the Ti content of the matrix and the transformation temperatures and favors the formation of an R-phase¹⁴. Therefore, the greater flexibility of the WOG can be attributed to the high Af temperatures and the two-stage specific transformation behavior, which

can be regarded as a dominant factor in this result.

The mechanical performance of the NiTi endodontic instrument may also affect the stress that is applied to the root canal wall during shaping. Whereas torque and apical force generation are essential for the removal of infected dentin, excessive torque/force may lead to the generation of a screw-in effect, which may increase the torsional fatigue and lead to a binding and separation of the instrument²⁵. In this study, maximum values for an upward apical force and CCW torque were obtained, both of which were generated by screw-in forces, and which were significantly smaller in the WOG Primary compared with the RE R25. However, there were no differences between the WOG Primary and WO Primary, which indicates that the metallurgical improvement and design/geometry modification in the WOG were insufficient to decrease the screw-in force that was generated during shaping.

The RE R25 showed the largest value for the upward apical force and CCW torque, which indicates that the highest screw-in forces were generated during preparation. This result may be related with its lower flexibility compared with the WOG Primary. Previous finite-element analysis showed that a more rigid file generates an increased screw-in force²⁶. Another explanation may be the nearly vertical pitch angle and the longest pith length of the RE, which may have resulted in the greatest reaction force in the file and the root canal wall among the three groups.

Apart from the mechanical differences of the file, the type of electrical motors may also influence the experimental results. Electrical motors have mechanical limitations for converting the rotation direction, resulting in acceleration and deceleration in both directions²⁹. It seems essential to choose an electrical motor that is appropriate for each type of file. In our study, the same electrical motor (X-SMART Plus) with different modes specified by the manufacturer was selected. Apical force and torque generation of reciprocating instruments driven with different motors requires further investigation. There are some limitations with the use of simulated canals because their physical properties are different from those of natural canals. However, standardized root canal shape and uniform canal wall hardness are essential for the comparison of apical force and torque¹². The straight canals with an open-type apical foramen in resin blocks were used in our experiments, because the curvature of the canals may have some influence on the measurement of apical force and torque. Since we adopted automated root canal instrumentation without irrigation during the whole preparation, the straight canal could reduce the potential risk of canal occlusion by debris.

CONCLUSIONS

The WOG Primary showed a significantly longer time to fracture than the WO Primary, smaller bending load values than the WO Primary and RE R25, and lower values of a maximum upward apical force and a maximum

CCW torque than the RE R25. Thus, the metallurgical improvements and design/geometry modifications in the WOG may confer a better fracture resistance and flexibility to this instrument, but are insufficient to decrease the screw-in force generation.

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