RESEARCH ARTICLE

Cyclic fatigue resistance of four different nickel-titanium instruments in an artificial canal [version 1; peer review: awaiting peer review]

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V1 First published: 13 Aug 2021, 10:800
<https://doi.org/10.12688/f1000research.55549.1>
Latest published: 13 Aug 2021, 10:800
<https://doi.org/10.12688/f1000research.55549.1>

Open Peer Review

Approval Status AWAITING PEER REVIEW

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Abstract

Introduction:

The objective of this study was to measure the number of cycles to fracture of four continuous or reciprocating rotary nickel-titanium instruments in different materials.

Methods:

A total of 40 nickel-titanium instruments were used for the present study. Instruments were divided into four groups (n=10): group 1, Revo-S SU; group 2, ProTaper Next X2; group 3, Reciproc R25; group 4, WaveOne Gold Primary. An artificial stainless-steel was used to test the cyclic fatigue of the instruments. The instruments were introduced into the stainless-steel canal, one at a time, until they reached the other end, then they were rotated inside the canal without in-out motion. The time from the beginning of instrument rotation until the occurrence of breakage was recorded. The number of rotated cycles to fracture of the instrument were calculated based on the revolutions per minute (rpm) of each instrument and the recorded rotated time. The mean number of cycles to fracture and standard deviations were calculated and statistically analysed.

Results:

The number of cycles to fracture of the Revo-S SU was the lowest, and that of the WaveOne Gold Primary was highest. Scanning electronic microscope images of fracture surfaces revealed the characteristics of fatigue.

Conclusions:

The number of cycles to fracture of the reciprocating WaveOne Gold Primary system was the highest amongst the tested instruments.

Keywords

cyclic fatigue, nickel-titanium, rotary, single-file, reciprocating

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Author roles: Pham KV: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Supervision, Validation, Writing – Original Draft Preparation, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: The author(s) declared that no grants were involved in supporting this work.

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How to cite this article: Pham KV. **Cyclic fatigue resistance of four different nickel-titanium instruments in an artificial canal [version 1; peer review: awaiting peer review]** F1000Research 2021, 10:800 <https://doi.org/10.12688/f1000research.55549.1>

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Introduction

To obtain successful results for endodontic treatment, clinicians must maintain the original anatomic configurations of the root canal systems without causing any mistakes.¹ Utilisation of nickel-titanium (NiTi) in rotary instruments was a revolution in root canal treatment and has become the standard for endodontic instrumentation.¹ The centring ability of these instrument systems in curved root canals was superior to that of manual instruments and the preparation time for nickel-titanium instruments was significantly less than manual instruments.^{2,3} Two of the best characteristics of these nickel-titanium instruments are their high flexibility and shape-memory ability. Although they have these good characteristics, these instruments seem to fracture easily in clinical application.⁴ There were two main causes of endodontic instrument breakage, cyclic fatigue and torsional stress although many other factors could affect this situation.⁵ In fatigue failure, the fatigue of the material leads to instrument fracture. Instead of being stuck in the root canal at one end, the instrument freely revolves in the curvature part of the canal.¹ When an instrument rotates in a curved canal at a static position, material around the curvature part of the canal is subjected to both tension and compression stress. The longer the time the instrument works within the curved canal, the more repeated tension/compression cycles the instrument endures. When the cyclic fatigue of the material exceeds the maximum threshold, the instrument breaks.⁶ To overcome the drawback of nickel-titanium instruments, the manufacturers continuously improve the rotary instrument in terms of design, materials, modes of rotation and techniques to minimise the number of fractured instruments.

The most popular mode of rotation for nickel-titanium instruments was continuous rotary. However, when rotated in curved canals, the instruments were subjected to cyclic fatigue, leading to the fracture of instruments. The multi-file NiTi systems require time consuming procedures because of the considerable number of files in the sets, including the glide path step in almost all current instruments. Nearly all conventional NiTi instruments have the same centres for rotational axis and geometric cross-section. The Revo-S system was the first instrument that possessed the off-centre design and recently, the ProTaper Next (PTN) was introduced. With the special off-centre design, Revo-S and PTN are two kinds of instruments with similar design and mode of continuous rotary rotation. With the eccentric rotary motion created by this new design of instrument, there were just two contacts between the instrument's edge and canal wall instead of three (Revo-S) or four (PTN) ones when compared to the conventional concentric design.^{7,8} The difference between these two instrument systems was the material used: conventional alloy for Revo-S or M-Wire alloy for PTN. M-Wire was developed by Tulsa Dental in 2007 with a special process in which Nitinol 508 was treated by exclusive heat procedure at various temperatures before grinding the blank wire.⁸ This new material contains both martensite and R phases, and PTN had high flexibility, fatigue resistance and needed less working time than the ProTaper Universal instrument did.⁸

The new single-file reciprocating technique was introduced first in 2008.⁹ Beside the main goal of this new instrumentation technique in improving the safety of the preparation stage, the other goals include decreasing instrumentation time, cost, and contamination risk of this phase. The balanced force technique was developed and modified to apply reciprocating motion to the new single-file NiTi instruments.¹⁰ Using only one file in the whole procedure, the certain single-file system could prepare the root canal system without the requirement of prior glide path preparation. The most popular single-file reciprocating systems in endodontics were Reciproc and WaveOne (Dentsply Sirona, Maillefer, Ballaigues, Switzerland). These two systems use the initial counter-clockwise movement to cut the dentin and clockwise movement to disengage the file from the dentin to avoid the screw-in effect and release the stress on the instrument.⁸ Both systems were made from the M-Wire alloy and claimed better cyclic fatigue resistance and good centre maintenance ability compared with the previous systems by the manufacturer.¹⁰ However, in the previous study, the WaveOne seemed worse in cyclic fatigue resistance when compared with the other systems because of its bigger cross-sectional area.¹¹ Recently, a new single-file reciprocating system was introduced using M-Wire with special gold heated treatment and improved cross-sectional design, named WaveOne Gold (WOG). Although having similar modes of rotation, Reciproc and WOG single-file systems possess different cross-sectional designs and materials: M-Wire for Reciproc and M-Wire with gold heated treatment for WOG. In the literature, there was limited information on the cyclic fatigue resistance of WOG.^{12,13}

The aim of this study was to evaluate the rotated cycles to failure of four different nickel-titanium instruments in an artificial canal: Revo-S, PTN, Reciproc, and WOG.

Methods

The following rotary nickel-titanium instruments were used in this study: Revo-S SU (Micro-Mega, Besançon, France), PTN X2 (Dentsply, Maillefer, Ballaigues, Switzerland), Reciproc R25 (VDW, Munich, Germany) and WOG (Dentsply, Maillefer, Ballaigues, Switzerland). All instruments were 21 mm long, size 25, taper of 0.06 (Revo-S SU and PTN X2), taper of 0.08 (Reciproc R25) and taper of 0.07 (WOG Primary). Each brand included ten instruments for the experiment. Revo-S SU is made of conventional NiTi alloy, PTN X2 and Reciproc are made of M-Wire alloy and WOG is made of M-Wire alloy with gold heat treatment. All instruments were in a new condition from the manufacturer and were inspected for any defects on the surfaces under stereomicroscope at 10 × magnification.

An artificial canal was made of tempered stainless steel to test the cyclic fatigue of these instruments. This device was described in detail in a previous study.¹⁴ A supporting system was also produced to serve the experiment. The supporting system included a horizontal table with fixed artificial canal device on it, a vertical standing system with brackets to grasp and adjust the endo-motor with a contra-angle (Figure 1). With this supporting system, the position of the instrument inside the contra-angle can be adjusted to coincide with the straight part of the artificial canal. The tempered stainless-steel canal was filled with RP7 (Selleys, Australia) to reduce the friction and heat. The instruments were inserted into the artificial canal until the tip of the instrument reached up to the terminus, all the brackets of the supporting system were tightly wrenched to fix the entire system. The instruments were then statically rotated inside the canal according to the manufacturers' parameters. The Revo-S SU, PTN X2, and Reciproc R25 were rotated at 300 rounds per minute (rpm), the WOG at 350 rpm, according to the manufacturers' instructions. The time was recorded from the beginning of rotation of the instrument until the instrument was fractured, this was a visual observation using a digital stopwatch at 1/100 exact level (Casio, Japan). From that time, the rotated cycles of the instrument were calculated based on the rpm used for each instrument. The mean number of cycles to fracture (NCF) and standard deviations were calculated and statistically analysed by SPSS version 20.0 (IBM, Armonk, NY, US) (RRID:SCR_019096) using the ANOVA and post-hoc Tukey tests at significance of 0.05 (An open-access alternative that can perform an equivalent function is the R Stats package (RRID:SCR_001905)). Fragments of instruments were analysed using a scanning electron microscope (SEM) (JSM 6510LV, JEOL, Tokyo, Japan) at 200 and 600 magnifications.

Results

Cyclic fatigue resistance test

The means and standard deviations for the NCF of each group are displayed in Table 1. The orders of NCF from lowest to highest were: Revo-S SU, PTN X2, Reciproc R25 and WOG Primary.¹⁵ The data were explored for normal distribution

Figure 1. Stainless-steel artificial canal with 6 mm radius.

Table 1. Means and standard deviations for the number of cycles to fracture (NCF) of each nickel-titanium instrument group in the experiment.

Group	Min	Max	Mean	SD	P
Revo-S SU	73.50	149.40	102.99 ^a	27.07	< 0.001*
PTN X2	309.90	457.65	372.89 ^b	54.21	
Reciproc R25	603.85	688.85	651.31 ^c	28.69	
WO Gold Primary	712.95	896.00	808.68 ^d	60.17	

PTN: ProTaper Next, WO: WaveOne, SD: Standard Deviation.

* $P < 0.05$, ANOVA test.

^{a,b,c,d} $P < 0.001$, Tukey Post Hoc Tests.

using the Shapiro-Wilk test. *P*-values for this test were greater than 0.05, therefore the data were distributed normally. Statistical analysis showed significant differences in NCF among all instruments using an ANOVA test.

SEM analysis

The fracture surface of instruments of different designs was similar. Analysis of the fragments under scanning electronic microscope showed that the fracture of the instruments was the result of fatigue (Figures 2A–C, 3A–C, 4A–C, and 5A–C).

Discussion

The present study used an artificial stainless-steel canal that was similar to other previous studies.^{13,14} Although the geometry of the artificial canal was not an appropriate fit to keep the instrument rotating on an absolutely exact trajectory, when compared to the other methods this artificial canal could control the position, radius, curvature, keep the instrument in a constant depth and at least change trajectory.¹⁶ One critical point of this study was that the instruments were tested in a static situation instead of a dynamic one. When used in dynamic rotation, in which the instruments were moved in and out

Figure 2A. Scanning electron microscopic surface images of the Revo-S SU (×200).

Figure 2B. Scanning electron microscopic surface images of the Revo-S SU (×600). The white arrow shows the crack initiation origin.

Figure 2C. Scanning electron microscopic surface images of the Revo-S SU ($\times 600$). The circled area depicts the overload fast fracture area.

Figure 3A. Scanning electron microscopic surface images of the ProTaper Next X2 ($\times 200$).

Figure 3B. Scanning electron microscopic surface images of the ProTaper Next X2 ($\times 600$). The white arrow shows the crack initiation origin.

Figure 3C. Scanning electron microscopic surface images of the ProTaper Next X2 ($\times 600$). The circled area depicts the overload fast fracture area.

Figure 4A. Scanning electron microscopic surface images of the Reciproc R25 ($\times 200$).

Figure 4B. Scanning electron microscopic surface images of the Reciproc R25 ($\times 600$). The white arrow shows the crack initiation origin.

Figure 4C. Scanning electron microscopic surface images of the Reciproc R25 ($\times 600$). The circled area depicts the overload fast fracture area.

Figure 5A. Scanning electron microscopic surface images of the WaveOne Gold Primary ($\times 200$).

Figure 5B. Scanning electron microscopic surface images of the WaveOne Gold Primary ($\times 600$). The white arrow shows the crack initiation origin.

Figure 5C. Scanning electron microscopic surface images of the WaveOne Gold Primary ($\times 600$). The circled area depicts the overload fast fracture area.

of the artificial canal, the instruments were more difficult to break than in static movement due to the stress being evenly distributed along the instrument's axis in the dynamic situation. However, dynamic rotation was very difficult to standardise and repeat for all instruments in the experiment.

The NCF of the Revo-S SU instrument in the present study was similar to that of a previous study because of the same artificial canal design. However, the NCFs of PTN, Reciproc and WO Gold were lower than those of previous studies.^{13,17} This result could come from the difference in the artificial canal curvatures. Therefore, the canal curvature was one of the many factors that can affect the cyclic fatigue resistance of the nickel-titanium instruments.

The results showed that the NCF of conventional NiTi Revo-S SU was lower than that of M-Wire ProTaper Next X2 even though both instruments have a similar off-centre cross-sectional design. This agrees with the results of many previous studies.^{17–19} The difference of cyclic fatigue resistance between the two instruments may come from the material. The Revo-S was made of conventional NiTi, while the ProTaper Next was made of M-Wire, a special material with premanufactured heat treatment from the company. Beside the M-Wire technology, the special off-centre design of the PTN might be an important factor in enhancing the strength of this instrument.¹⁷

In the present study, the cyclic fatigue resistance of ProTaper Next was lower than that of Reciproc, although both instruments had the same construction material. However, these two instruments have different cross-sectional designs. With an off-centre cross-sectional design, the ProTaper Next had some advanced features in reducing the friction between the instrument and dentinal surface and increasing the space between the instrument and canal wall for easier removal of the dentine shavings.⁷ The Reciproc with the S-shaped cross-section had only two contacts between the instrument and canal wall, therefore, reducing the friction and increasing the cyclic fatigue resistance.⁸ The mode of rotation was one of the important reasons for this result. The ProTaper Next used continuous rotation, while the Reciproc used reciprocating rotation. Reciprocating rotation, at the beginning, was introduced to reduce the torsional stress that the instruments endured when working inside the root canal, decreasing the failure because of torsional breakage.²⁰ Previous studies proved that reciprocating rotation extended the cyclic fatigue life of the instrument.^{9,21} All current single-file reciprocating systems are recommended as single-use instruments.

The cyclic fatigue resistance of WOG was highest in this study. The new cross-section of the WOG was different from the previous WaveOne instrument. The bigger cross-section area of the WaveOne resulted in the worse cyclic fatigue of this instrument compared with the fatigue resistance of Reciproc.¹¹ The new ellipsoidal patented cross-section with four cutting edges but only a contact edge with the canal wall, in associating with the specific constant rake angle on the cutting part of the instrument, decreases the friction contact and annuls almost completely the screw-in effect between the instrument and the canal wall.⁸ The difference of NCF between Reciproc and WOG may also come from the construction material, although both instruments had the same mode of rotation. The WOG was made of M-Wire but experienced the post-manufactured heat treatment. The manufacturer claims that this special procedure makes the WOG stronger and more flexible than WaveOne systems. To influence the transformation behaviour of NiTi alloys, heat treatment or thermomechanical treatment is the main method used by manufacturers. Depending on the thermomechanical treatment

that the manufacturer used, single-stage (austenite [A] and martensite [M]) or two-stage transformation (A-R-M: three phases included in the transformation: austenite, R, and martensite) will happen inside the material to create the near-equiatomic NiTi alloys.²⁰ Normally, single-stage transformation from A to M happens inside the material to create nickel-rich NiTi alloys. With the special heat procedure, finely dispersed Ti₃Ni₄ is created, which precipitates in the austenitic matrix, and the material will show two-stage A-R-M transformation. When applied stress exceeds the critical level, NiTi alloys undergo phase transformation because of the super-elasticity or pseudo-elasticity.²² By modifying the transformation temperatures (austenitic start and austenitic finish) of WOG files by special post-manufactured heat treatment better properties can be created for the instruments.²³

Up to now, there were two modes of observation to detect the fracture mechanism of endodontic instruments: direct fractured surface and lateral view. With the lateral view mode, some studies used magnifying loupes, an operating microscope, and SEM with low magnification to examine the fracture.^{24–26} However, this method appeared to fail in revealing the actual fracture mechanism of instruments.²⁷ There were some specific signs on the fractured surface that could only be observed under SEM at high magnification, which revealed the actual fracture mechanism of instruments, but not in lateral view.²⁷

Scanning electronic microscope analysis showed that there was evidence of fatigue breakage. There were two specific areas on the fracture surface: crack initiation origin area and the overload fast fracture area. The peripheral area was smooth and featureless, while the overload fast fracture area was the remaining large area that showed a dimpled surface. The micrographs were like those of previous studies.^{1,4,28} In the fatigue process, when the crack develops, the area of sound material was reduced at that cross-section. When the remaining material was subjected to stress that exceeds its maximum strength (as the stress is inversely proportional to the cross-sectional area with the even load) at the next load cycle, the alloy fractures in a ductile manner and a dimple configuration was created.²⁷

Conclusions

Within the limitations of this *in vitro* study, the cyclic fatigue resistance of the WaveOne Gold Primary single-file system was the highest amongst the tested instruments.

Data availability

Underlying data

Mendeley Data: Underlying data for ‘Cyclic fatigue resistance of four different nickel-titanium instruments in an artificial canal’, <https://www.doi.org/10.17632/ngzppdf5z.1>.¹⁵

This project contains the following underlying data:

- Data File: Khoa Cyclic Fatigue.xlsx

Data are available under the terms of the [Creative Commons Attribution 4.0 International license](#) (CC-BY 4.0).

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