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Original

Comparison of cyclic fatigue and torsional resistance in reciprocating single-file systems and continuous rotary instrumentation systems

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Abstract: As compared with continuous rotary systems, reciprocating motion is believed to increase the fatigue resistance of NiTi instruments. We compared the cyclic fatigue and torsional resistance of reciprocating single-file systems and continuous rotary instrumentation systems in simulated root canals. Eighty instruments from the ProTaper Universal, WaveOne, MTwo, and Reciproc systems (*n* = 20) were submitted to dynamic bending testing in stainless-steel simulated curved canals. Axial displacement of the simulated canals was performed with half of the instruments (*n* = 10), with back-and-forth movements in a range of 1.5 mm. Time until fracture was recorded, and the number of cycles until instrument fracture was calculated. Cyclic fatigue resistance was greater for reciprocating systems than for rotary systems ($P < 0.05$). Instruments from the Reciproc and WaveOne systems significantly differed only when axial displacement occurred ($P < 0.05$). Instruments of the ProTaper Universal and MTwo systems did not significantly differ ($P > 0.05$). Cyclic fatigue and torsional resistance were greater for reciprocating systems than for continuous rotary systems, irrespective of axial displacement.
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Keywords: rotary instrumentation; cyclic fatigue; reciprocity.

Introduction

Development of nickel-titanium (NiTi) endodontic instruments started a revolution in biomechanical preparation of root canal systems (1). These instruments have a lower elasticity modulus than conventional stainless steel files and are therefore more flexible (2). This greater flexibility, combined with other favorable mechanical properties and high cutting efficiency, increases the safety and effectiveness of instrumentation of curved canals without causing deviation in the final preparation shape (2).

Despite the ease of use and clinical efficiency of NiTi files, this type of instrumentation system can result in

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complications and accidents (3). Unexpected fracture of instruments in the absence of visible signs of cutting blade deformation has been reported (3). Fracture of NiTi instruments used in continuous rotary motion can be caused by torsion or cyclic fatigue (4). Torsional fracture occurs when the tip or another part of the instrument is locked in the canal while the other parts continue to rotate (4). The instrument tip fractures when torque exceeds the elastic limit of the metal (5).

When the instrument is used for instrumentation in curved canals, compression force and tensile stress are alternately generated on each part of the instrument (6). Continuous repetition of these forces can cause instrument fracture (7). Cyclic fatigue refers to the number of cycles an instrument can support; a good instrumentation system must be able to withstand stress fracture at more than 1,000 cycles (7).

To increase the fracture resistance of instruments, new fabrication processes have been developed in the production of NiTi alloys (8). M-Wire alloy is prepared using a differential thermal process that can substantially increase the flexibility and mechanical strength of NiTi instruments (9). In addition to new alloys, NiTi instruments with different kinematics, such as reciprocating motion, have longer life spans and greater cyclic fatigue resistance (10).

Recently, M-Wire alloy was used in the development of two new instrumentation systems that are specifically designed to be used with reciprocating motion: the Reciproc (VDW GmbH, Munich, Germany) and WaveOne (Dentsply/Maillefer, Ballaigues, Switzerland) (11). Both these systems comprise three instruments: the R25, R40, and R50 (the Small, Primary, and Large Files, respectively). The main difference between the instruments in these systems is the gradual increase in the diameter of the active tip (12).

These single-use instruments are designed to prevent fracture from prolonged use (12). However, single-use instruments are used in one tooth, even if the tooth has three or four root canals, as in the case of molars, and are suitable for curved and atretic canals (12). Studies suggest that a disadvantage of single-use instruments is excessive tensile and compression forces on the instrument, which occur with instruments in continuous rotary systems and can cause fracture (13,14).

The aim of this study was to evaluate cyclic fatigue and torsional resistance of instruments from four different systems—two continuous rotary systems (ProTaper Universal and MTwo) and two reciprocating systems (Reciproc and WaveOne)—in simulated curved canals with and without axial displacement. The null hypothesis tested was that there would be no difference between these systems, irrespective of movement kinematics or axial displacement.

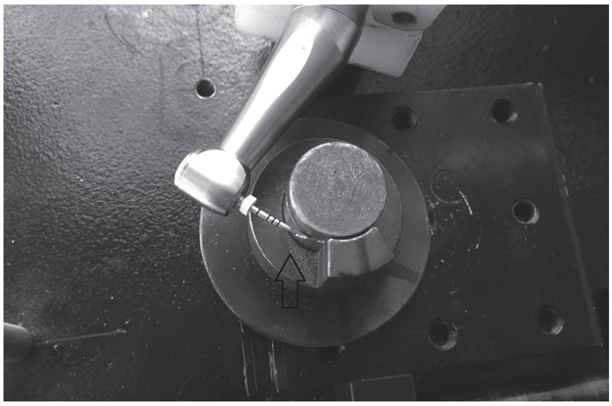

Fig. 1 Artificial canal with an angle of curvature of 45° and a radius of 5 mm. The instrument is positioned for the dynamic bending test (arrow).

Materials and Methods

Eighty NiTi instruments (length, 25 mm) from four different instrumentation systems (*n* = 20 per system) were used in this study, as follows: the R25 (Reciproc; VDW GmbH, Munich, Germany), Primary File (WaveOne; Dentsply/Maillefer, Ballaigues, Switzerland), F2 (ProTaper Universal; Dentsply/Maillefer), and 25.06 (MTwo; VDW). All instruments were submitted to dynamic bending testing in a device simulating an artificial canal with an angle of curvature of 45° and radius of curvature of 5 mm (Fig. 1).

Testing device

The device used for the tests consisted of an iron base (50 × 30 cm) supported by four rubber feet, to prevent vibration during testing. A fixing support for the low-speed handpiece (Dabi Atlante S/A Indústrias Médico Odontológicas, Ribeirão Preto, SP, Brazil) and artificial canal was placed on the base.

During the dynamic bending test, the low-speed handpiece remained in a fixed position, held by brackets bolted to the iron base. The support holding the low-speed handpiece had a mechanism for vertical and horizontal adjustment, to allow movement in all directions. After the instruments had been coupled to the low-speed handpiece, the height of the support was adjusted so that the instrument could be inserted in a straight trajectory into the artificial canal, without causing stress and allowing free rotation.

The curvature of the stainless-steel artificial canal was

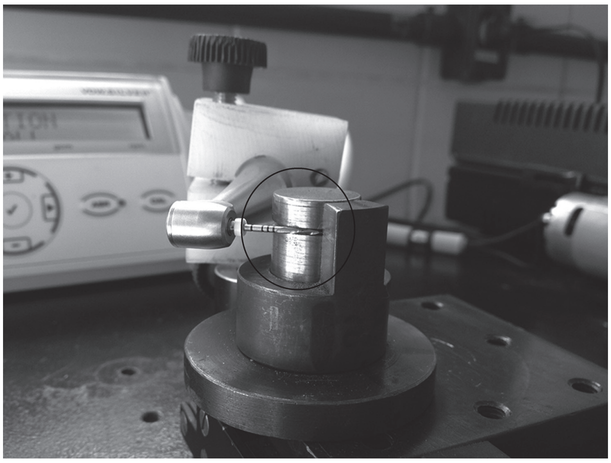

Fig. 2 The stainless-steel artificial canal has a 1-mm-deep groove located 5 mm from the top, which is designed to guide the instrument during axial displacement (circle).

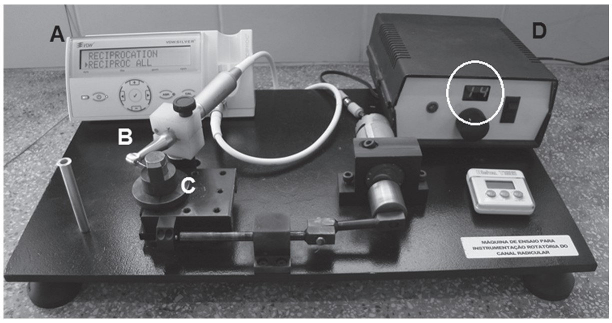

Fig. 3 The device used for cyclic fatigue and torsional resistance testing (upper view). A. Reciproc Silver (VDW) electric motor; B. Low-speed handpiece; C. Artificial canal; and D. Potentiometer. The number selected on the digital display ("14") indicates the speed of axial displacement of the simulated canal (142 displacements per minute) (circle).

fitted onto a cylinder guide made of the same material (angle of curvature, 45°; radius, 5 mm). The simulated canal permitted axial movements of the instruments. The standardized axial movement was 142 displacements per minute.

Both the arch and guide cylinder had a 1-mm-deep groove located 5 mm from the top, to match the height of the low-speed handpiece. The groove served as a guide path for the instrument, which remained curved and free to rotate between the cylinder and external arch.

To establish the point of maximum curvature, at approximately 4 mm from the tip, the position of the instruments in the artificial canal was set by determining the area of the instrument that is exposed to more-severe cyclic deformation conditions during biomechanical preparation of curved root canals. During the tests, the instruments were placed so that about 1 mm of the instrument tip protruded beyond the end of the artificial canal walls, which allowed visualization of the tip extremities and facilitated determination of the precise moment of instrument fracture. Thus, the timer and electric motor were activated at exactly the same time.

Dynamic bending test

The instruments were powered by the Reciproc Silver (VDW) electric motor at a controllable speed and torque. The motor was operated at a constant speed of 280 rpm and a torque of 230 gcm for continuous rotary systems. For reciprocating instruments, the WAVEONE ALL mode was selected for instruments in the WaveOne system and the RECIPROC ALL mode was used for instruments in the Reciproc system.

The time from motor activation to instrument fracture was recorded on a digital timer. The number of cycles was obtained by multiplying the rotation speed of continuous rotary instruments (280 rpm), divided by 60 (seconds), by the time elapsed until instrument fracture. For reciprocating systems, the value for time until fracture was multiplied by 10, since the electric motor performed 10 cycles per second for reciprocating instruments. In half of the tested instruments (n = 10), the device was activated, which promoted axial displacement of the simulated canal. With the instrument properly positioned, the main switch was turned on. A set composed of a low-speed handpiece/instrument was powered by the pneumatic system to reproduce the pecking motion, with back-and-forth movements in a range of 1.5 mm in each direction (forward or backward). Each instrument slid through a 1-mm-deep groove, which served as a guide path during instrumentation. Axial movement was simultaneously activated when the low-speed handpiece was activated in half of the instruments tested (Figs. 2 and 3).

The length of fractured instrument fragments was measured with a digital caliper (Digimess, São Paulo, SP, Brazil).

Statistical analysis

The normality of the data distribution was tested by the Kolmogorov-Smirnov test, and values obtained in the cyclic fatigue test were statistically compared (two-way ANOVA, Bonferroni's test, $P < 0.05$) with the aid of the Minitab 14.1 software program (Minitab; Quality. Analysis. Results., State College, PA, USA).

Results

The mean number of cycles performed and time until

Table 1 Mean (±SD) number of cycles to fatigue fracture (n = 10)

	Groups			
	ProTaper	MTwo	Reciproc	WaveOne
No axial displacement	6,904.7 ± 709.0^{a,A}	1,731.8 ± 592.8^{b,A}	23,881.0 ± 4,115.8^{c,A}	18,210.0 ± 8,153.0^{c,A}
With axial displacement	2,044.1 ± 397.3^{a,A}	1,546.0 ± 199.4^{a,A}	37,294.0 ± 2,972.1^{b,B}	28,307.0 ± 8,072.6^{c,B}

Lowercase letters compare data in the same row and uppercase letters compare data in the same column.
Groups with the same letter do not significantly differ (level of significance = 5%).
Two-way ANOVA, Bonferroni's test, $P < 0.05$
$P = 0.08$

Table 2 Mean (±SD) time (in s) until instrument fracture (n = 10)

	Groups			
	ProTaper	MTwo	Reciproc	WaveOne
No axial displacement	1,501.0 ± 154.1^{a,A}	376.4 ± 128.8^{b,A}	2,388.1 ± 745.6^{c,A}	1,821.0 ± 815.3^{ac,A}
With axial displacement	444.3 ± 86.3^{a,B}	336.1 ± 43.3^{a,A}	3,729.4 ± 313.3^{b,B}	2,830.7 ± 807.2^{c,B}

Lowercase letters compare data in the same row and uppercase letters compare data in the same column.
Groups with the same letter do not significantly differ (level of significance = 5%).
Two-way ANOVA, Bonferroni's test, $P < 0.05$
$P = 0.05$

Table 3 Mean (±SD) length (in mm) of fractured instrument fragment (n = 10)

	Groups			
	ProTaper	MTwo	Reciproc	WaveOne
No axial displacement	2.32 ± 0.58^{a,A}	3.09 ± 0.14^{a,A}	7.27 ± 0.32^{b,A}	7.07 ± 1.13^{b,A}
With axial displacement	2.31 ± 0.62^{a,A}	3.37 ± 0.97^{b,A}	7.63 ± 0.47^{c,A}	7.80 ± 0.33^{c,A}

Lowercase letters compare data in the same row and uppercase letters compare data in the same column.
Groups with the same letter do not significantly differ (level of significance = 5%).
Two-way ANOVA, Bonferroni's test, $P < 0.05$
$P = 0.03$

instrument fracture are shown in Tables 1 and 2, respectively.

The number of cycles before fracture was significantly higher for reciprocating instruments than for rotary instruments, regardless of whether axial displacement occurred during instrumentation of the simulated canal ($P < 0.05$). When axial displacement occurred, the Reciproc system had the greatest resistance to cyclic fatigue, followed by the WaveOne system ($P < 0.05$ for both). However, the systems did not significantly differ ($P > 0.05$) when axial displacement did not occur. In contrast, continuous rotary systems significantly differed only when axial displacement did not occur ($P < 0.05$).

Time until fracture was greater for reciprocating systems than for rotary systems, irrespective of axial displacement. However, when axial displacement did not occur, the WaveOne and ProTaper systems had statistically similar results ($P > 0.05$).

The average fragment length was significantly shorter for rotary systems than for reciprocating instruments under both instrumentation conditions ($P < 0.05$) (Table 3).

Discussion

This study evaluated cyclic fatigue and torsional resistance of rotary instruments with different movement kinematics. On the basis of the results, the null hypothesis was rejected, since cyclic fatigue and torsional resistance were greater for instruments from reciprocating systems than for those from continuous rotary systems, irrespective of axial displacement during instrumentation.

Instrumentation systems with reciprocal kinematics were developed to allow root canal shaping with a single instrument (12,15). Treatment simplification reduces root canal treatment time and cost (15). However, because only a single instrument is used, considerable force is exerted on the instrument during biomechanical preparation (12).

In this study we used a device that simulates a root canal with a radius of curvature of 5 mm and an angle of curvature of 45°, which is considered a critical angle for instrumentation (16). The simulated canal allows instruments to be activated and work freely, without exposure to compression or tensile forces. Furthermore, the device can be used to promote axial displacement of instruments, which simulates the clinical conditions of in-and-out movement of the instrument inside the root canal.

The Reciproc and WaveOne systems have instruments with blades designed to cut in a counterclockwise direction (12,17). The degree of rotation in the clockwise and counterclockwise directions is different. Higher rotation occurs in the counterclockwise direction, which corresponds to the cutting direction, causing advancement of the instrument in the canal and removing dentin (18). However, the instrument rotates at a smaller angle of rotation in the clockwise direction, which allows it to unlock and move safely through the root canal, thereby reducing the risk of instrument fracture (18).

These angles of rotation are specific for each system and were determined with respect to the torsional properties of each instrument (17). Thus, the aim of reciprocating motion is to decrease the risk of torsional fracture, since the angle of counterclockwise rotation is designed to be smaller than the elastic limit of the instrument (19). Moreover, the instrument needs to perform only a few movements around its axis to complete a rotation of 360° (19).

Cyclic fatigue resistance is defined as the number of cycles an instrument can bear before fracturing during a test (20). The number of cycles performed is cumulative and is related to the intensity of stress generated by compression and tensile forces in the curved portion of the instrument during instrumentation (20). Several studies have shown that fracture time is also related to the speed of instrument rotation: instruments are more resilient when operating at lower speeds (21).

In this study, both reciprocating and continuous rotary motion were powered by the Reciproc Silver (VDW) electric motor. The operating modes selected for the WaveOne and Reciproc systems were similar to those used in clinical conditions. These modes are pre-programmed, and the operator has no influence on the speed or torque of the instruments.

According to the manufacturers, the Reciproc system rotates in clockwise and counterclockwise directions at a speed of approximately 300 rpm, with a difference of 120° between the two movements (22,23). The WaveOne system is similar to the Reciproc system, but rotational speed is higher, 350 rpm (18,22,23). Although the rotational speed of the continuous rotary system is lower (280 rpm), rotational speed during reciprocating motion is not constant, as the electric motor has certain mechanical limitations in converting rotation direction, unlike what occurs with continuous rotary systems (11). Thus, the process of acceleration and deceleration in both rotation directions generates less tension on the instrument and therefore provides greater cyclic fatigue resistance (21), as observed in the present study. Furthermore, according to Gavini et al. (22), the RECIPROC ALL mode performs 10 cycles of reciprocating motion per second, i.e., 3.33 revolutions per second. Thus, the RECIPROC ALL mode rotates at a speed of 200 rpm (3.33 revolutions per second), not 300 rpm, as stated by the manufacturer. This confirms the findings of Li et al. (21) and Kim et al. (11), who found that instruments used at a lower speed were more resistant to fatigue fracture. However, the manufacturer of the WaveOne system provides no information on how many cycles of reciprocating motion per second the system is able to perform (18).

Although the two reciprocating systems used in this study were made from the same M-Wire alloy, they have different cross-sections. The Reciproc instruments have an S-shaped design, and the WaveOne files have a triangular concave blade cross-section (11). Several studies have shown that instruments with larger cross-sectional areas have greater flexibility and torsional stiffness (17,19) and, consequently, greater resistance to torsion and cyclic fatigue (19). However, our results contradict the findings of earlier studies. According to Kim et al. (11), the WaveOne Primary File has a cross-sectional area of 323 μm^2, the Reciproc R25 instrument has an area of approximately 275 μm^2, and the F2 ProTaper Universal instrument has an area of 318 μm^2. If only the cross-sectional areas of the instruments of the different systems is considered, the ProTaper and WaveOne should have the greatest cyclic fatigue resistance. However, in a comparison of the reciprocating and continuous rotary system, the alloy used to manufacture the reciprocal instruments (M-Wire) has a greater effect on the mechanical strength of the instruments, due to its flexibility (9).

Despite the greater cross-sectional area of the WaveOne instruments, the files had significantly less cyclic fatigue resistance than Reciproc when there was less axial displacement in the simulated canal during instrumentation. This finding suggests that back-and-forth movement of the device—to simulate the in-and-out movement of the instrument within the root canal—was important in the performance of the WaveOne system.

Cyclic fatigue of an instrument occurs mainly when it rotates in a curved canal at maximum flexure, during which continuous tension and compression cycles substantially increase torsional stress, causing fracture (22). Instruments fractured due to excessive torque during biomechanical preparation show signs of plastic deformation (24). According to Gavini et al. (22), torsional resistance was greater for the WaveOne system than for the Reciproc system; however, fractographic analysis of the fractured surface of fragments showed characteristic signs of failure due to shear forces, including circular abrasion marks and skewed dimples in the center of rotation. Furthermore, Gavini et al. (22) found that the WaveOne system was more suitable for atretic canals because of its higher torsional resistance and lower flexural resistance, while the Reciproc system was best suited for instrumentation of curved canals because of its greater flexural resistance. In this study, axial displacement exerted during instrumentation of the simulated canal generated shear forces on the bent area of the instrument, which also contribute to progressive plastic deformation and fracture (25), as observed with the WaveOne.

Fragments from fractured instruments were significantly longer for reciprocating systems than for continuous rotary systems, which contradicts the results of Kim et al. (11), who observed that the length of such fragments was similar, irrespective of the results from cyclic fatigue and torsional resistance testing and instrument movement kinematics. After dynamic bending testing, they observed similar crack initiation zones and overload (fast fracture) areas in fractured instruments from the different systems. Moreover, both systems exhibited characteristic cyclic fatigue and torsional fractures on fractography, regardless of where the fracture had occurred in the instrument. This finding indicates that reciprocating systems can delay but not prevent fracture of the instrument by cyclic fatigue.

Our results indicate that cyclic fatigue and torsional resistance were greater for reciprocating systems than for continuous rotary systems, irrespective of axial displacement. However, further clinical studies should be conducted to examine the effectiveness of these instruments in biomechanical preparation of root canals and their effect on reducing fracture risk.

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