10.5005/jp-journals-10024-2016

ORIGINAL RESEARCH

Flute and Shank Dimensions of Reciprocating Instruments before and after Simulated Root Canal shaping

[1]Felipe C Sampaio, [2]Ana PP Brito, [3]Heloisa HP Veloso, [4]Ana HG de Alencar, [5]Daniel de A Decurcio
[6]José AP de Figueiredo, [7]Carlos Estrela

ABSTRACT

Aim: This study analyzed the effect of the dimensions of the flute and shank in the first 4 mm of instrument tips on the deformation and dimensional changes of reciprocating instruments after root canal shaping (RCS).

Materials and methods: The reciprocating instruments used were Reciproc® R25, R40, and R50; WaveOne® Small, Primary, and Large; and Unicone® #20, #25, and #40. Scanning electron microscopy images of the first 4 mm of the tip were acquired at 30× magnification before and after simulated curved root canals were shaped. Each instrument was used only once. The images were transferred to the AxioVision® software to measure the flute area (μm^2), shank area (μm^2), flute length (μm), and cross-sectional diameter (μm). Student's t test for paired samples was used to compare differences before and after RCS, and analysis of variance followed by the Tukey test, to compare differences between instruments of similar sizes. The instruments were classified according to deformations after RCS.

Results: Reciproc® instruments had larger flutes and smaller shanks. The Reciproc® R40 had significant differences in cross-sectional diameter at 0.5 mm from the tip. Reciproc® had no plastic deformations. Unicone® #20 instruments had significant differences in cross-sectional diameter at 1.5 and 3.0 mm from the tip, and #25 instruments had differences at 1.5 and 3.0 mm and in length of the second and third flutes. One #20 and three #40 instruments had plastic deformations. The differences in length of the first and fourth flutes of WaveOne® Primary and in cross-sectional diameter at 2.0 mm from the tip of WaveOne® Large were significant. Two of three WaveOne® Large instruments had plastic deformations.

Conclusion: Reciproc® instruments had greater flute areas and lengths and smaller shanks than Unicone® and WaveOne® instruments of similar sizes. Reciproc® instruments had a greater flute-to-shank ratio. WaveOne® instruments had the lowest flute-to-shank ratio. Unicone® instruments had the most plastic deformations. Instruments with larger flutes and smaller shanks had fewer plastic deformations after curved RCS.

Clinical significance: The knowledge of mechanical behavior before choosing the endodontic instrument may avoid fracture, regardless of the clinical condition, and it is essential to the success of root canal treatment.

Keywords: Endodontic instruments, Flute, Laboratory research, Plastic deformation, Reciprocating instruments, Root canal shaping.

How to cite this article: Sampaio FC, Brito APP, Veloso HHP, Alencar AHG, Decurcio DA, Figueiredo JAP, Estrela C. Flute and Shank Dimensions of Reciprocating Instruments before and after Simulated Root Canal shaping. J Contemp Dent Pract 2017;18(3):198-204.

Source of support: CAPES

Conflict of interest: None

[1,2]Department of Endodontics, School of Dentistry, Instituto Tocantinense Presidente Antônio Carlos, Porto Nacional Tocantins, Brazil

[3]Department of Endodontics, School of Dentistry, Federal University of Paraíba, João Pessoa, Paraíba, Brazil

[4,5,7]Department of Stomatological Sciences, School of Dentistry Federal University of Goiás, Goiânia, Goiás, Brazil

[6]Clinical Department, School of Dentistry, Pontifical Catholic University of Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil

Corresponding Author: Felipe C Sampaio, Department of Endodontics, School of Dentistry, Instituto Tocantinense Presidente Antônio Carlos, Porto Nacional, Tocantins Brazil, e-mail: felipecavalcantisampaio@yahoo.com drfelipecavalcanti@gmail.com

INTRODUCTION

The control of microorganisms depends on effectiveness of root canal, regardless of the clinical condition of the pulp.[1] Cleaning and shaping should include irrigation strategies and the mechanical action of endodontic instruments. A perfectly shaped root canal is a refined standard for optimal endodontic and coronal sealing.[2]

The choice of instrument for root canal shaping (RCS) may be a challenge for endodontists. The preservation of the original shape and position of the apical foramen when using a nonflexible instrument for curved RCS is complex and often difficult, especially during canal enlargement, which should respect root canal anatomy.[3,4] Therefore, several studies have evaluated the use of new nickel–titanium (NiTi) instruments and found that they are much more flexible than stainless steel instruments.[5] They are safe for RCS using continuous rotation because of their advanced manufacturing process and characteristics of use.[6] However, they may undergo plastic deformation during RCS, which may lead to instrument fracture, one of the major problems during RCS.[7] To avoid deformation, different morphological characteristics, such as cross-sections,[8] surface treatment,[9] and thermal treatments,[10] have been developed.

Reciprocating NiTi instruments[11] are currently used for RCS. A handpiece for reciprocation was invented in the 1960s,[12] but did not add any greater benefit to manual RCS for the instruments available at the time.[13]

The reciprocating motion, which consists of a counterclockwise movement followed by a shorter clockwise movement before the complete rotation, reduces NiTi instrument fracture.[11,14] It enhances cyclic fatigue resistance because it avoids bending of the instrument tip against root canal walls, which results in better resistance to torsional fracture.[14-22] Moreover, their thermal treatment during manufacture due to chemical composition changes improves their mechanical properties. The most reciprocating instruments are manufactured at the martensite phase, which improves flexibility and reduces instrument failure.[23]

Despite these advantages, reciprocating instruments also undergo deformation and fracture. In a study that evaluated 1,696 Reciproc® instruments used clinically only once, a few R25 instruments separated (0.47%) or underwent deformation (0.35%).[24] Another clinical study evaluated 2215 WaveOne® instruments used only once and found that three instruments separated in the apical third.[25]

The mechanical behavior of instruments during RCS may affect the prognosis of endodontic treatments. Several studies found microcracks after RCS using reciprocating instruments, most of them in the apical third.[22-25] The morphological features of their working area may affect their resistance and mechanical behavior.[26-29] Biz and Figueiredo[30] evaluated the association between flute and shank dimensions in the area of the first, third, and fifth flute of ProFile .04, ProFile .06, Pow-R .02, Pow-R .04, and Quantec 2000 instruments and found that shank-to-flute ratios were proportional for all the instruments. Quantec 2000 had larger flutes compared with the other instruments, which may reinforce their structure in this area of the instruments.

Several instrument types are available in the market, and dentists should consider each instrument characteristics and how these characteristics affect their mechanical behavior before choosing the instrument for each clinical condition. The flute and shank designs and dimensions of endodontic reciprocating instruments differ, and it is therefore, important to evaluate the association of these parameters with instrument plastic deformation. This study evaluated the effect of the dimensions of the first 4 mm of the flute and shank on the occurrence of plastic deformations and dimensional changes in reciprocating instruments used for RCS.

MATERIALS AND METHODS

Sample Selection

Reciprocating instruments of different tapers and origins were used for the evaluation of flute and shank dimensions: Reciproc® R25 #25/.08, R40 #40/.06, and R50 #50/.05 (VDW GmbH, Munich, Germany); Unicone® #20/.06, #25/.06, and #40/.06 (Medin, Nové Město na Moravě, Czech Republic); WaveOne® Small #21/.06, Primary #25/.08, and Large #40/.08 (Dentsply Maillefer, Ballaigues, Switzerland). Three instruments of each type were used (n = 27).

Image Acquisition before RCS

The reciprocating instruments were fixed in 5.5 cm diameter stubs before use. The surface images of each instrument were acquired using a scanning electron microscopy (SEM) unit (Jeol; JSM 6610, Tokyo, Japan). The images of the first 4 mm of the tip of the instruments were acquired at 30× magnification and 7 kV tension in two positions: (A) Flat surface (concave) of the attachment section and (B) convex surface of the attachment section (LabMic, Federal University of Goiás, Goiania, Brazil).

Root Canal Shaping

The instruments were rinsed under running water, placed in the ultrasonic cleaning unit for 3 minutes, and then dried with sterile gauze. For RCS, 27 simulated and standardized curved root canals (0.18 mm of apical limit diameter and 15 mm long) (IM do Brasil Ltda., São Paulo, Brazil) were used. The simulated root canals were irrigated with 5 mL of 2.5% sodium hypochlorite during RCS. Root canals were prepared with a single instrument and an electric motor (X-Smart® Plus; Dentsply Maillefer, Ballaigues, Switzerland). The Reciproc program was used for Reciproc® instruments, and the WaveOne program for WaveOne® and Unicone® instruments. The WaveOne program was selected for Unicone® instruments because Unicone® instrument numbers are similar to those of the WaveOne® system and because there is no specific program for Unicone® instruments in X-Smart® Plus. After RCS, the instruments were cleaned as described earlier.

Image Acquisition after RCS

The instruments were fixed in stubs, and images of their tips were acquired using SEM at 30× magnification and 7 kV tension (LabMic, UFG) as previously described.

Analysis of SEM Images

The SEM images were transferred to the software AxioVision® (Carl Zeiss Microscopy GmbH, Jena, Germany) to measure instrument dimensions and analyze deformations after use, defined as shape changes in the working area of the instrument and deformation of instrument flutes, and to compare them with the images acquired before use. First, flute areas (μm^2) were measured between the points where the flute met the upper and lower helical grooves (Fig. 1A). The flutes were always positioned in the upper part of the image to standardize measurements, and each had to be fully seen in the 4 mm from the tip of the instrument. The shank area was 4 mm from the tip, and the lateral limits for measurement were the same points used to determine flute area. The lower limit was the tip and the upper limit was the point 4 mm from the tip (Fig. 1B).

In addition, flute length was measured from the upper to the lower points where the flute met the helical grooves (Fig. 1C). Measurements were recorded in micrometers (μm). Diameter was measured at 0.5, 1, 1.5, 2, 2.5, 3, 3.5, and 4 mm from the tip (μm) (Fig. 1D).

Statistical Analysis

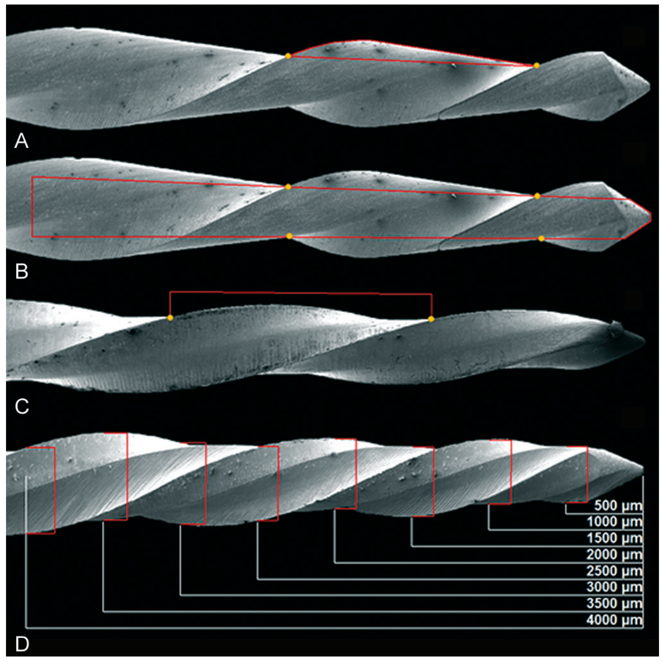
The data about the plastic deformation of instrument surfaces were descriptively analyzed using frequency tables and including only the number of instruments with plastic deformation, not the number of deformations or their characteristics.

Student's t test for paired samples was used to compare measurements before and after use.

Instruments numbers #25 (Reciproc R25, Unicone #25, and WaveOne Primary) and #40 (Reciproc R40, Unicone #40, and WaveOne Large) were compared between systems using analysis of variance and the Tukey test.

RESULTS

The SEM images revealed that there were plastic deformations in the flutes of one Unicone® #20, three Unicone® #40, and two WaveOne® Large instruments. The measurements confirmed structural changes after RCS. Reciproc® instruments had larger flutes and smaller shanks. Only Reciproc® R40 instruments had significant differences in cross-sectional diameter at 0.5 mm from the tip ($p < 0.05$). Unicone® #20 instruments had significant differences ($p < 0.05$) in cross-sectional diameter at 1.5 and 3 mm from the tip and in the length of the second and third flutes. Shank area after use was significantly different in Unicone® #25. The lengths of the first and fourth flutes were significantly different in WaveOne® Primary instruments. Significant differences were also found in the cross-sectional diameter at 2 mm from the tip of the WaveOne® Large instruments. The other measurements had no significant differences. There were also no significant differences in the cross-sectional diameter at 1.0, 2.5, and 4 mm from the tip between Reciproc® R25, Unicone® #25, and WaveOne® Primary before and after RCS (Table 1). The differences of cross-sectional diameter at 1.5, 2.5, and 4 mm from the tip between Reciproc® R40, Unicone® #40, and WaveOne® Large before and after RCS were also not statistically significant (Table 2).



Figs 1A to D: (A) Flute area. Yellow points, at intersection of flute and helical groove, are upper (farthest from tip) and lower (closer to tip) limits; (B) shank area. Yellow points used for flute measurements are also lateral limits for shank measurement. Shank was measured from tip to 4 mm (area under study); (C) flute length. Yellow points, at intersection of flute and helical groove, are upper (farthest from tip) and lower (closer to tip) limits; and (D) cross-sectional diameters measured at each 0.5 mm (500 μm) from tip. A reference ruler was developed from scale on SEM image to determine measurement area and points where diameters should be measured

DISCUSSION

The reciprocating instruments included in this study, Reciproc®, WaveOne®, and Unicone®, have different diameters, taper, and cross-sections. These differences

Table 1: Reciproc® R25, Unicone® #25, and WaveOne® Primary before and after RCS

Variable	*Reciproc® R25 before*	*Reciproc® R25 after*	*Unicone #25 before*	*Unicone #25 after*	*WaveOne primary before*	*WaveOne primary after*
Flute area 1	34871.30^{A}	34498.15^{A}	17780.56^{BC}	19802.78^{C}	11400.00^{BD}	10145.37^{D}
Flute area 2	52392.59^{A}	52155.55^{A}	26574.08^{BC}	30200.00^{C}	16420.37^{D}	16930.56^{BD}
Shank area	976682.41^{A}	973281.48^{A}	1102911.11^{B}	1086040.74^{B}	1259451.85^{C}	1264200.00^{C}
Diameter 0.5 mm	187.00^{A}	182.52^{A}	268.80^{B}	272.80^{B}	263.81^{B}	266.02^{B}
Diameter 1.0 mm	299.51^{A}	294.53^{A}	291.76^{A}	287.32^{A}	287.80^{A}	284.46^{A}
Diameter 1.5 mm	247.18^{A}	254.41^{A}	301.12^{B}	303.90^{B}	329.50^{C}	328.37^{C}
Diameter 2.0 mm	357.28^{A}	333.66^{A}	320.53^{B}	319.42^{B}	363.66^{A}	366.43^{A}
Diameter 2.5 mm	365.02^{A}	374.43^{A}	348.47^{A}	351.25^{A}	391.75^{A}	391.74^{A}
Diameter 3.0 mm	365.31^{A}	364.57^{A}	369.19^{A}	370.85^{A}	413.81^{B}	418.27^{B}
Diameter 3.5 mm	483.86^{A}	473.77^{A}	397.25^{B}	394.50^{B}	438.80^{C}	437.69^{C}
Diameter 4.0 mm	401.23^{A}	419.02^{A}	423.88^{A}	425.55^{A}	453.31^{A}	451.62^{A}
Flute length 1	1059.89^{A}	1048.20^{A}	938.98^{B}	925.89^{B}	725.87^{C}	742.89^{C}
Flute length 2	1242.84^{A}	1226.44^{A}	1098.74^{B}	1094.84^{B}	890.55^{C}	895.26^{C}

*Capital letters (A, B, C and D) indicate statistically significant differences

Table 2: Reciproc® R40, Unicone® #40, and WaveOne® Large before and after RCS

Variable	*Reciproc® R40 before*	*Reciproc® R40 after*	*Unicone® #40 before*	*Unicone® #40 after*	*WaveOne® Large before*	*WaveOne® Large after*
Flute area 1	76051.85^{AB}	81265.74^{B}	73115.74^{ABC}	99125.93^{B}	43952.78^{C}	48920.37^{AC}
Shank area	1111100.00^{A}	1108128.70^{A}	1386538.89^{B}	1376334.26^{B}	1490857.41^{C}	1511757.41^{C}
Diameter 0.5 mm	288.12^{A}	355.35^{B}	356.64^{B}	354.99^{B}	355.45^{B}	370.44^{B}
Diameter 1.0 mm	369.05^{B}	321.80^{B}	396.14^{A}	392.83^{A}	402.95^{A}	404.06^{A}
Diameter 1.5 mm	380.57^{A}	384.95^{A}	417.85^{A}	418.97^{A}	426.18^{A}	431.73^{A}
Diameter 2.0 mm	395.66^{A}	443.41^{AB}	450.46^{AB}	439.90^{AB}	467.03^{B}	451.47^{AB}
Diameter 2.5 mm	445.95^{A}	378.76^{A}	463.51^{A}	461.30^{A}	489.47^{A}	486.80^{A}
Diameter 3.0 mm	442.44^{A}	444.16^{A}	490.51^{AB}	485.74^{AB}	520.00^{B}	513.85^{B}
Diameter 3.5 mm	425.39^{A}	517.03^{B}	515.60^{B}	516.72^{B}	542.78^{B}	543.34^{B}
Diameter 4.0 mm	516.69^{A}	502.79^{A}	541.97^{A}	523.86^{A}	571.35^{A}	564.45^{A}
Flute length 1	1368.57^{AB}	1395.60^{AB}	1646.23^{BC}	1959.14^{C}	1175.57^{A}	1756.72^{AB}

*Capital letters (A, B, C and D) indicate statistically significant differences

may result in different resistance and mechanical behaviors. Reciproc® instruments have larger flutes and greater flute-to-shank ratios, whereas WaveOne® instruments have lower flute-to-shank ratios. None of the three sizes of Reciproc® instruments underwent any plastic deformation but they all had some changes in dimensions after RCS. These results are similar to those found in a clinical study[24] and confirm that reciprocating instruments are safe for RCS when used once.

Reciproc® instruments are S-shaped, WaveOne® instruments are triangular and have concavities near flute, and Unicone® instruments are triangular and have convex helical grooves. Schäfer and Tepel[31] evaluated the effect of cross-section and number of flutes on fracture of rotary NiTi instruments. The resistance to torsional fracture and to cyclic fatigue of S-shaped instruments increased with number of flutes, but number of flutes did not affect the resistance to fracture of triangular instruments. Our study found that Reciproc® instruments had fewer flutes, which may improve resistance to cyclic fatigue because of their S-shaped cross-section. WaveOne® and Unicone® had more flutes, but this may not affect resistance to fracture because of their triangular cross-sections. However, a greater flute area may reinforce their structure.[30] Reciproc® had greater flute areas than WaveOne® and Unicone®, which may have contributed to the fact that Reciproc® had fewer plastic deformations after curved RCS.

The evaluation of fracture resistance of Reciproc® R40 and WaveOne® Large revealed that the first had greater resistance to cyclic fatigue.[18,32] The comparison of Reciproc® R25 and WaveOne® Primary revealed that WaveOne® had worse cyclic fatigue results.[33] These results are similar to those reported in other studies:[18,32,33] WaveOne® instruments had more dimensional changes after use, and two of the three WaveOne® Large instruments had deformations.

The results of this study and the knowledge about the structure of endodontic instruments[30,31] suggest Reciproc® instruments may have higher resistance to cyclic fatigue due to their larger flute area and length and their shorter shank. The longer shank of WaveOne® may provide greater resistance to torsional fracture.

Plotino et al[34] evaluated the cutting efficiency of Reciproc® R25 and WaveOne® Primary and found that Reciproc® R25 had a greater cutting efficiency than

WaveOne® Primary. Reciproc® larger flutes may contribute to their greater cutting efficiency, especially because of their association with an S-shaped cross-section.

These results may define the choice of an instrument for each type of root canal. Endodontists should understand how the morphological characteristics of an instrument may affect its properties so that they make the best choice for each clinical case. Reciproc® seems to be a safer choice for a highly curved root canal, whereas WaveOne® may provide better results for a straighter canal. Unicone® instruments may be more susceptible to failure due to more deformations and dimensional differences and of all the instruments analyzed should not be the first choice.

However, any adequate choice of endodontic instruments should consider all other characteristics that may affect resistance and be associated with root canal morphology, operator experience, instrument cross-section, and kinematics.[35-37] The number of uses should not be a key factor in instrument choice because despite the effect of use on plastic deformation and fractures, sterilization and reuse of the instruments are not recommended for two of the systems under evaluation, Reciproc® and WaveOne®.

The NiTi alloy currently used has minor variations in chemical composition and undergoes different heat treatments to improve its mechanical properties. For example, the alloy in the martensite reorientation stage, called M-Wire, has greater flexibility under stress and is less likely to fracture.[23] The Reciproc® and WaveOne® instruments are manufactured using M-Wire. Unicone® also undergoes heat treatment, but the manufacturer does not specify the stage. The use of M-Wire should provide a safer RCS with reciprocating systems.

The root canal should be enlarged within anatomical limits, regardless of instrument properties or technique applied. The greatest diameter of the apical third at 1 mm from the apex of the root canals of permanent premolars is 0.18 to 0.37 mm, and of molars, 0.19 to 0.45 mm.[38] Ran et al[39] evaluated the penetration of *Enterococcus faecalis* in dentinal tubules of single-rooted teeth prepared to #30 instruments under different conditions. The microorganisms penetrated 435 μm into the dentin of the apical third, 322 μm at low-alkaline pressure (pH = 9.0) and 100 μm at pH 10. Anatomical and microbiological features should be considered to define the minimal enlargement of the apical third with instruments of a higher diameter than the one specified by the manufacturer for reciprocating instruments (D_0 = 0.25 mm).

This study found that all the instruments underwent dimensional changes after shaping of a root canal of D_0 = 0.18 mm, although some of these changes were not statistically significant. The instruments were used in curved root canals of the same D_0 (0.18 mm) to evaluate and understand the dimensional changes of these instruments after RCS. Although used in root canals different from those recommended, instruments #50 did not have plastic deformations. WaveOne® and Unicone® #40 instruments had more plastic deformations than the other instruments of the same systems. Because of this need to enlarge the root canal to a size greater than the one recommended by the manufacturer, as explained above, and the high number of microfractures, more than one instrument of the reciprocating system, in increasing sizes, should be used to ensure greater safety and avoid plastic deformations and fractures, as well as to achieve optimal RCS. This study evaluated the area of the instrument closer to the tip (4 mm) because this is where most instrument fractures[25] and dentinal microcracks[26-29] occur.

The simulated root canals were used to standardize the diameter along the entire length of the canals. The results of this study are similar to those of previous studies, despite the limitations of simulated root canals.[18,24,31-37,40,41]

The method used in this study successfully detected plastic deformations of endodontic instruments. Some plastic deformations were not detected by measuring the dimensions because of the position of the external surface, but were visible under SEM magnification. At the same time, measurements were useful to detect morphological changes that are less evident to the eye.

The AxioVision® software was used in a previous study[42] for the accurate external delimitation of areas. The 30× magnification ensured that measurements were accurate and that instrument plastic deformations were visualized. Biz and Figueiredo[30] found that 60× magnification was accurate for measurements of abraded surfaces of flute and shank, and this method was effective to calculate the shank-to-flute ratio at the flute site. The structures in the first 4 mm from the tip were accurately measured at 30× magnification.

Instrument structures should be carefully evaluated because they may directly affect mechanical behavior during shaping of the complex root canal system. The characteristics under evaluation in this study suggest that Reciproc® has greater flexibility and resistance to cyclic fatigue. WaveOne® has less flexibility and greater shank resistance and resistance to torsional fracture. Studies should further investigate the mechanical behavior of reciprocating instruments and how their design and dimensions may affect their properties during use.

CONCLUSION

Reciprocating instruments had dimensional changes after curved RCS. Reciproc® instruments had a greater flute area and length and a shorter shank than Unicone®

and WaveOne® instruments of similar sizes. Unicone® instruments had a greater number of plastic deformations detected under SEM. Greater flute dimensions and smaller shank dimensions were associated with fewer plastic deformations after RCS.

REFERENCES

1. Schilder H. Cleaning and shaping the root canal. Dent Clin North Am 1974 Apr;18(2):269-296.
2. Estrela C, Holland R, Estrela CR, Alencar AH, Sousa-Neto MD, Pécora JD. Characterization of successful root canal treatment. Braz Dent J 2014 Jan-Feb;25(1):3-11.
3. Lopes HP, Elias CN, Estrela C, Siqueira JF Jr. Assessment of the apical transportation of root canals using the method of the curvature radius. Braz Dent J 1998;9(1):39-45.
4. Liu SB, Fan B, Cheung GS, Peng B, Fan MW, Gutmann JL, Song YL, Fu Q, Bian Z. Cleaning effectiveness and shaping ability of rotary ProTaper compared with rotary GT and manual K-Flexofile. Am J Dent 2006 Dec;19(6):353-358.
5. Walia HM, Brantley WA, Gerstein H. An initial investigation of the bending and torsional properties of Nitinol root canal files. J Endod 1988 Jul;14(7):346-351.
6. Peters OA, Barbakow F, Peters CI. An analysis of endodontic treatment with three nickel-titanium rotary root canal preparation techniques. Int Endod J 2004 Dec;37(12):849-859.
7. Wang NN, Ge JY, Xie SJ, Chen G, Zhu M. Analysis of Mtwo rotary instrument separation during endodontic therapy: a retrospective clinical study. Cell Biochem Biophys 2014 Nov;70(2):1091-1095.
8. Haapasalo M, Shen Y. Evolution of nickel-titanium instruments: from past to future. ETP Endod Topics 2013 Sep;29(1): 3-17.
9. Lopes HP, Elias CN, Vieira VT, Moreira EJ, Marques RV, de Oliveira JC, Debelian G, Siqueira JF. Effects of electropolishing surface treatment on the cyclic fatigue resistance of BioRace nickel-titanium rotary instruments. J Endod 2010 Oct;36(10):1653-1657.
10. Shen Y, Zhou HM, Zheng YF, Peng B, Haapasalo M. Current challenges and concepts of the thermomechanical treatment of nickel-titanium instruments. J Endod 2013 Feb;39(2):163-172.
11. Yared G. Canal preparation using only one Ni-Ti rotary instrument: preliminary observations. Int Endod J 2008 Apr;41(4):339-344.
12. Frank AL. An evaluation of the Giromatic endodontic handpiece. Oral Surg Oral Med Oral Pathol 1967 Sep;24(3):419-421.
13. Spyropoulos S, Eldeeb ME, Messer HH. The effect of Giromatic files on the preparation shape of severely curved canals. Int Endod J 1987 May;20(3):133-142.
14. Lopes HP, Elias CN, Vieira MV, Siqueira JF Jr, Mangelli M, Lopes WS, Vieira VT, Alves FR, Oliveira JC, Soares TG. Fatigue life of Reciproc and Mtwo instruments subjected to static and dynamic tests. J Endod 2013 May;39(5):693-696.
15. De-Deus G, Moreira EJ, Lopes HP, Elias CN. Extended cyclic fatigue life of F2 ProTaper instruments used in reciprocating movement. Int Endod J 2010 Dec;43(12):1063-1068.
16. Wan J, Rasimick BJ, Musikant BL, Deutsch AS. A comparison of cyclic fatigue resistance in reciprocating and rotary nickel-titanium instruments. Aust Endod J 2011 Dec;37(3):122-127.
17. Gavini G, Caldeira CL, Akisue E, Candeiro GT, Kawakami DA. Resistance to flexural fatigue of Reciproc R25 files under continuous rotation and reciprocating movement. J Endod 2012 May;38(5):684-687.
18. De-Deus G, Leal Vieira VT, Nogueira da Silva EJ, Lopes H, Elias CN, Moreira EJ. Bending resistance and dynamic and static cyclic fatigue life of Reciproc and WaveOne large instruments. J Endod 2014 Apr;40(4):575-579.
19. Jin SY, Lee W, Kang MK, Hur B, Kim HC. Single file reciprocating technique using conventional nickel-titanium rotary endodontic files. Scanning 2013 Nov-Dec;35(6):349-354.
20. Pedullà E, Grande NM, Plotino G, Gambarini G, Rapisarda E. Influence of continuous or reciprocating motion on cyclic fatigue resistance of 4 different nickel-titanium rotary instruments. J Endod 2013 Feb;39(2):258-261.
21. Kiefner P, Ban M, De-Deus G. Is the reciprocating movement per se able to improve the cyclic fatigue resistance of instruments? Int Endod J 2014 May;47(5):430-436.
22. Shin CS, Huang YH, Chi CW, Lin CP. Fatigue life enhancement of NiTi rotary endodontic instruments by progressive reciprocating operation. Int Endod J 2014 Sep;47(9): 882-888.
23. Zhou H, Peng B, Zheng, YF. An overview of the mechanical properties of nickel-titanium endodontic instruments. Endod Topics 2013 Sep;29(1):42-54.
24. Plotino G, Grande NM, Porciani PF. Deformation and fracture incidence of Reciproc instruments: a clinical evaluation. Int Endod J 2015 Feb;48(2):199-205.
25. Cunha RS, Junaid A, Ensinas P, Nudera W, Bueno CE. Assessment of the separation incidence of reciprocating WaveOne files: a prospective clinical study. J Endod 2014 Jul;40(7): 922-924.
26. Bürklein S, Tsotsis P, Schäfer E. Incidence of dentinal defects after root canal preparation: reciprocating versus rotary instrumentation. J Endod 2013 Apr;39(4):501-504.
27. Arias A, Lee YH, Peters CI, Gluskin AH, Peters OA. Comparison of 2 canal preparation techniques in the induction of microcracks: a pilot study with cadaver mandibles. J Endod 2014 Jul;40(7):982-985.
28. Jamleh A, Komabayashi T, Ebihara A, Nassar M, Watanabe S, Yoshioka T, Miyara K, Suda H. Root surface strain during canal shaping and its influence on apical microcrack development: a preliminary investigation. Int Endod J 2015 Dec;48(12): 1103-1111.
29. Karatas E, Gündüz HA, Kirici DÖ, Arslan H, Topçu MÇ, Yeter KY. Dentinal crack formation during root canal preparations by the twisted file adaptive, ProTaper Next, ProTaper Universal, and WaveOne instruments. J Endod 2015 Feb;41(2): 261-264.
30. Biz MT, Figueiredo JA. Morphometric analysis of shank-to-flute ratio in rotary nickel-titanium files. Int Endod J 2004 Jun;37(6):353-358.
31. Schäfer E, Tepel J. Relationship between design features of endodontic instruments and their properties. Part 3. Resistance to bending and fracture. J Endod 2001 Apr;27(4):299-303.
32. Kim HC, Kwak SW, Cheung GS, Ko DH, Chung SM, Lee W. Cyclic fatigue and torsional resistance of two new nickel-titanium instruments used in reciprocation motion: Reciproc versus WaveOne. J Endod 2012 Apr;38(4):541-544.
33. Higuera O, Plotino G, Tocci L, Carrillo G, Gambarini G, Jaramillo DE. Cyclic fatigue resistance of 3 different nickel-titanium reciprocating instruments in artificial canals. J Endod 2015 Jun;41(6):913-915.

34. Plotino G, Giansiracusa Rubini A, Grande NM, Testarelli L, Gambarini G. Cutting efficiency of Reciproc and WaveOne reciprocating instruments. J Endod 2014 Aug;40(8):1228-1230.
35. Hülsmann M, Peters OA, Dummer PM. Mechanical preparation of root canals: shaping goals, techniques and means. Endod Topics 2005 Mar;10(1):30-76.
36. Cheung GS. Instrument fracture: mechanisms, removal of fragments, and clinical outcomes. ETP Endod Topics 2009;16(1):1-26.
37. McGuigan MB, Louca C, Duncan HF. Endodontic instrument fracture: causes and prevention. Br Dent J 2013 Apr;214(7): 341-348.
38. Wu MK, R'oris A, Barkis D, Wesselink PR. Prevalence and extent of long oval canals in the apical third. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2000 Jun;89(6): 739-743.
39. Ran S, Wang J, Jiang W, Zhu C, Liang J. Assessment of dentinal tubule invasion capacity of *Enterococcus faecalis* under stress conditions ex vivo. Int Endod J 2015 Apr;48(4):362-372.
40. Plotino G, Grande NM, Testarelli L, Gambarini G. Cyclic fatigue of Reciproc and WaveOne reciprocating instruments. Int Endod J 2012 Jul;45(7):614-618.
41. Ha JH, Kim SR, Versluis A, Cheung GS, Kim JW, Kim HC. Elastic limits in torsion of reciprocating nickel-titanium instruments. J Endod 2015 May;41(5):715-719.
42. Machado R, Silva Neto UX, Ignácio SA, Cunha RS. Lack of correlation between obturation limits and apical leakage. Braz Oral Res 2013 Jul-Aug;27(4):331-335.