Comparative evaluation of mechanical properties and shaping performance of heat-treated nickel titanium rotary instruments used in the single-length technique

Taro NAKATSUKASA, Arata EBIHARA, Shunsuke KIMURA, Keiichiro MAKI, Miki NISHIJO, Daisuke TOKITA and Takashi OKIJI

Department of Pulp Biology and Endodontics, Division of Oral Health Sciences, Graduate School of Medical and Dental Sciences, Tokyo Medical and Dental University (TMDU), 1-5-45 Yushima, Bunkyo-ku, Tokyo 113 8549, Japan
Corresponding author, Arata EBIHARA; E-mail: a.ebihara.endo@tmd.ac.jp

This study aimed to evaluate the mechanical properties of contemporary heat-treated nickel-titanium (NiTi) rotary instruments used in the single-length technique [ProTaper Next (PTN), HyFlex EDM (EDM), and JIZAI (JZ)]. Bending loads, cyclic fatigue resistance, torque/force values and canal-centering ratios were evaluated for the three instruments and a non-heat-treated experimental NiTi instrument with the same geometry as JZ (nJZ). EDM and JZ exhibited significantly lower bending load and more cycles to failure compared with nJZ and PTN (p<0.05). PTN and JZ exhibited significantly better centering ability than nJZ and EDM (p<0.05). JZ and nJZ generated significantly smaller upward force and maximum torque than PTN and EDM (p<0.05). Under the present experimental condition, JZ exhibited flexibility and cyclic fatigue resistance comparable to EDM, better maintained the canal curvature than the other instruments, and generated smaller torque and screw-in force than PTN and EDM.

Keywords: Heat treatment, Nickel-titanium rotary instrument, Torque, Fracture resistance, Screw-in force

INTRODUCTION

Nickel-titanium (NiTi) rotary instruments have become popular owing to their superior flexibility\(^1\) and canal-centering ability\(^2\) compared with stainless steel instruments. However, intracanal separation remains a concern during the clinical use of the NiTi instruments, particularly in narrow and curved canals. Many technological advancements have been made to prevent inadvertent fracture and develop more efficient NiTi rotary systems that can preserve the original canal curvature, including changes to the cross-sectional design\(^3\), motion\(^4\) and metallic property\(^5\). In particular, heat treatment changes the phase transformation temperature of the NiTi alloy, which results in the growth of soft and ductile phases, i.e., the martensite phase and R-phase, thereby enhancing the fracture resistance and flexibility\(^6\). Moreover, owing to the improvement of flexibility and fracture resistance, several contemporary NiTi instruments are recommended for use with the single-length technique, where every instrument is brought to the full working length in a designated sequence, usually in order from small- to large-sized instruments. The single-length technique is claimed by the manufacturers to be efficient and more easy-to-learn compared with the traditional crown-down technique.

ProTaper Next (PTN; Dentsply Sirona, Ballaigues, Switzerland) is a widely-studied single-length NiTi rotary system manufactured from M-Wire, which is produced by a proprietary heat treatment of a NiTi alloy (55.8% Ni and 44.2% Ti by weight) and possesses an austenite finish temperature of 43–50°C\(^7,8\). At room or body temperature, this alloy contains martensite and R-phase and shows enhanced flexibility and cyclic fatigue resistance compared with conventional austenitic NiTi wires\(^9\). PTN has a variable taper (increasing and decreasing percentages) and off-center rectangular cross-sectional design. The manufacturer claims that the design of the PTN aims to decrease the points of contact between the file and canal wall and to improve the fatigue resistance by minimizing the stresses that might accumulate on the file.

HyFlex EDM (EDM; Coltene-Whaledent, Allstätten, Switzerland) is another contemporary single-length NiTi rotary system, which is made of a NiTi alloy containing less Ni (52% by weight) than conventional NiTi alloys\(^10\) and manufactured using electro-discharge machining followed by a post-machining thermal treatment\(^11\). Due to the heat treatment-induced shift of the austenite starting temperature to around 43°C, EDM contains substantial amount of R-phase and martensite at either room or body temperature\(^12,13\). Thus, unlike austenitic NiTi instruments, EDM shows bending deformation at room or body temperature. EDM has different cross sections along the cutting surface (triangular near the handle, trapezoidal in the middle portion and rectangular near the tip). The instrument with a tip size of 0.25 mm (OneFile) has a variable taper (0.08 taper in the apical 4 mm, 0.06 taper in the middle portion and 0.04 taper near the handle). EDM exhibits superior flexibility\(^14\) and cyclic fatigue resistance\(^15,16\) compared with M-Wire instruments.

JIZAI (JZ; MANI, Tochigi, Japan) is a newly developed NiTi rotary system made of a proprietary heat-treated NiTi alloy. The phase composition of JZ has not yet been reported, but JZ shows bending deformation...
like EDM, indicating that JZ is not purely austenitic but contains R-phase and/or martensite at room or body temperature. JZ has an off-center quasi-rectangular cross-section with a radial land on one of the short sides (Fig. 1). The manufacturer claims that such a cross-sectional shape generates low screw-in forces owing to the radial land and provides wide spaces for debris removal. The recommended sequence for severely curved canals consists of two instruments in a single-length technique, where a #25/0.04 taper instrument followed by a #25/0.06 taper instrument are used sequentially for the full working length.

The single-length technique is reported to produce higher torsional stress compared with the traditional crown-down technique due to smaller amount of coronal enlargement. This suggests that inadvertent use of the single-length technique leads to the generation of screw-in force and an increased risk of intracanal instrument separation. Thus, mechanical property and shaping performance of the single-length NiTi rotary systems should be thoroughly evaluated to assure safe clinical use of these systems. Therefore, this study aimed to evaluate the flexibility, cyclic fatigue resistance, torque and vertical force, and canal-centering ability of the contemporary single-length NiTi rotary instruments, i.e., PTN, EDM and JZ, with the same tip size. A non-heat-treated experimental NiTi instrument with the same geometry as JZ (termed nJZ) was also examined for comparison. The null hypothesis was that there would be no difference in the tested mechanical properties among the four instruments.

MATERIALS AND METHODS

Test instruments
PTN (X2; #25/0.06–0.07 taper), EDM (OneFile; #25/0.08–0.04 taper), JZ (#25/0.06 taper) and nJZ (#25/0.06 taper) were used for the bending and dynamic cyclic fatigue tests. For the evaluation of torque/force and canal-centering ability, two files were used in each system as described below. The rotation speed was set at 300 rpm for PTN, 400 rpm for EDM, and 500 rpm for JZ and nJZ, according to the manufacturers’ recommendation.

Bending test
The instruments (n=10, each) were subject to a cantilever-bending test as previously described. Briefly, the instruments were fixed 7.0 mm from the tip, loaded (1.0 mm/min) to a position 2 mm from the tip until the displacement reached 3.0 mm, and then unloaded. The bending loads at displacements of 0.5 and 2 mm were evaluated.

Dynamic cyclic fatigue test
The testing device consisted of a test stand (MH2-500N, IMADA, Aichi, Japan) with a moving stage to which the handpiece of an endodontic motor (X-Smart Plus, Dentsply Sirona) was attached. A stainless steel artificial canal with a 1.5-mm diameter, a 60° angle of curvature and a 3.0-mm radius of curvature was used. The center of the curvature was located 5 mm from the tip of the instrument. The instruments (n=10, each) were rotated in the canal, while the handpiece moved with a 2-mm back-and-forth motion at 5 mm/s. Silicone oil (KF-96-100CS, Shin-Etsu Chemical, Tokyo, Japan) was used as a lubricant. The time to fracture was recorded, and the number of cycles to failure (NCF) was calculated as rpm×time to failure (min).

Evaluation of torque and vertical force
Forty J-shaped simulated resin root canal models (Endo Training Bloc, Dentsply Sirona) were flared to a depth of 4 mm from the apex using a ProTaper SX instrument (Dentsply Sirona), and a glide path was created with #10–20 stainless steel K-files (Zipperer, Munich, Germany). The models were then randomly assigned to four test instruments (n=10, each). Each model was instrumented with a custom-made, automated root canal instrumentation and torque/force analyzing device previously described. Briefly, the device consisted of an endodontic motor (J Morita, Kyoto, Japan), a test stand (MX2-500N, IMADA), and a torque/force measuring unit where a load cell (LUX-B-ID, Kyowa, Tokyo, Japan) and strain gauges (KFG-2-120-D31-11, Kyowa) were installed to measure the apical/coronal vertical loads and clockwise torque, respectively. The model was connected to the torque/force measuring unit. The handpiece attached to the moving stage of the stand was programmed to repeat an up-and-down movement at 50 mm/min for 2 and 1 s in the apical and coronal direction, respectively. The maximum values were recorded.

Instrumentation was performed using two-instruments, single-length instrumentation sequences according to the manufacturers’ recommendation; X1 (#17/0.04–0.075 taper) followed by X2 in PTN; #20/0.05 taper followed by OneFile in EDM; and #25/0.04 taper followed by #25/0.06 taper in JZ and nJZ. The working lengths were set incrementally at 14 and 16 mm (full working length) for the first instrument and 14, 15 and 16 mm for the second instrument. Following each
instrumentation, the patency was checked using a #10 K-file, and canals were irrigated with 1 mL of distilled water. RC-Prep (Premier Dental, Plymouth Meeting, PA, USA) was used as a lubricant.

Canal-centering ability
Pre- and post-instrumentation images of the root canal models were taken with a digital microscope (VH-8000, Keyence, Osaka, Japan), and superimposed with image processing software (Photoshop 7.0, Adobe Systems, San Jose, CA, USA). The canal-centering ratio 0, 0.5, 1, 2, and 3 mm from the apex was calculated by the following formula: (amount of resin removed from the outer side-amount of resin removed from the inner side)/post-instrumentation canal diameter. In this formula, a value of 0 indicates perfect centering.

Statistical analysis
Data were analyzed using SPSS Statistics 23.0 (IBM, Armonk, NY, USA). Two-way repeated measures analysis of variance (ANOVA) was used to analyze bending loads, torque/force values and centering ratios, and the main effect and interaction of the independent variables were confirmed. If both were significant, the simple main effect was tested and if it was significant, all pairwise comparisons were made with the Bonferroni test. One-way ANOVA and the Bonferroni test were used to compare the NCF. A p-value<0.05 was considered statistically significant.

RESULTS

Bending load
Two-way ANOVA showed that two factors, “instruments” and “measuring points”, influenced the bending loads (p<0.05) with significant interactions (p<0.05). At a 0.5-mm deflection, JZ and nJZ exhibited significantly greater bending loads than EDM and PTN (p<0.05; Fig. 2A). At a 2.0-mm deflection, EDM and JZ exhibited significantly lower bending loads than the others (p<0.05; Fig. 2A).

Dynamic cyclic fatigue value
As shown in Fig. 2B, EDM and JZ exhibited significantly greater cyclic fatigue values than nJZ and PTN (p<0.05). There was no significant difference between EDM and JZ (p>0.05).

Canal-centering ratio
According to two-way ANOVA, “instruments” and “measuring points” influenced the centering ratio (p<0.05) with significant interactions (p<0.05). JZ showed significantly the lowest centering ratio among all instruments at 0 mm (p<0.05); PTN and JZ showed significantly lower centering ratios than EDM and nJZ at 0.5, 1 and 2 mm (p<0.05; Fig. 3).

Torque and vertical force
According to two-way ANOVA, “instruments” and “instrumentation sequence (1st or 2nd)” influenced the maximum torque and vertical force values (p<0.05). There was significant interaction between the two factors (p<0.05).

In the 1st instrumentation, EDM and JZ showed significantly smaller upward force than the other instruments (p<0.05; Fig. 4A). In the 2nd instrumentation, JZ and nJZ showed significantly smaller upward force than the others (p<0.05; Fig. 4A).

The maximum downward force values were PTN<JZ and nJZ in the 1st instrumentation (p<0.05), and EDM<JZ and nJZ in the 2nd instrumentation (p<0.05;
Fig. 3 Canal centering ratio 0, 0.5, 1, 2, and 3 mm from the apex. Data represent the mean and standard deviation (n=10). The different capital letters indicate the centering ratio values are significantly different (p<0.05) within the same measuring point. The different lowercase letters indicate the centering ratio values are significantly different (p<0.05) within the same instrument.

Fig. 4 The maximum values of (A) upward force, (B) downward force and (C) torque during root canal instrumentation. Data represent the mean and standard deviation (n=10). The different capital letters are considered significantly different (p<0.05) within the same instrumentation sequence (1st or 2nd). The different lowercase letters are significantly different (p<0.05) within the same instrument.

Fig. 4B). The maximum torque in the 1st instrumentation was not significantly different among the instruments (p>0.05; Fig. 4C). In the second instrumentation, JZ and nJZ showed significantly smaller torque than the others (p<0.05; Fig. 4C).

No instrument deformation or fracture occurred during the experiment.

DISCUSSION

The present study demonstrates that the four NiTi rotary instruments made of differently heat-treated alloy exhibited several significant differences in terms of the tested properties, when instruments with the same tip size were compared. Thus, the null hypothesis was rejected.

The comparison of JZ and nJZ excluded the influence of the instrument geometry and clearly demonstrated the improvement in the flexibility, cyclic fatigue resistance, canal-centering ability and upward force by heat treatment. This agrees with several studies where instruments with identical geometry are compared\textsuperscript{1,22-24}. However, the torque was similar for JZ and nJZ, which is in line with our previous finding that Reciproc and Reciproc Blue generated similar torque\textsuperscript{24},
and suggests that torque is not greatly dependent on the heat treatment-induced metallurgical differences but can be influenced by other factors such as instrument geometry.

In the bending test, loads at 0.5 and 2.0 mm correspond to elastic and superelastic ranges, respectively20. Thus, JZ exhibited a superelastic property that is comparable to EDM and more pronounced than PTN and nJZ. This is most likely attributed to the heat treatment-induced changes of the phase transformation temperature, which resulted in the growth of the soft and ductile martensite and R-phases, and accelerated stress-induced martensitic transformation28. The austenite finish temperature of M-Wire is reported as 43–50°C17,28. Thus, PTN is not completely austenitic but contains small amounts martensite and R-phase at room or body temperature. In contrast, EDM consists of martensite, R-phase and a small amount of austenite, as indicated by its austenite starting temperature (appropriately 43°C)12,13. Such difference in phase composition may account for the present results that EDM showed a lower bending load than PTN in the superelastic range. The phase transformation temperature of JZ has not yet been reported, but the manufacturer claims that JZ contains a considerable amount of R-phase. This may be attributed to the result that the bending load of JZ was similar to that of EDM in the superelastic range. In contrast, the bending loads of JZ and nJZ in the elastic range were greater than those of PTN and EDM, which may be because JZ and nJZ have a wider cross-sectional area and core diameter than PTN and EDM. Such features are known to increase the stiffness20,27.

This study employed a dynamic cyclic fatigue test with a pecking motion that better simulates the clinical condition and induces stress distribution through a certain length of the blade20. Although there are no standardized specifications, a 2-mm pecking distance was chosen to facilitate comparison with a previous study20. An up-and-down speed of 50 mm/min was chosen based on a previous study21. Clinically, however, the pecking distance and speed are controlled manually and can be variable even within an operator. A low frequency of pecking motion is recommended to reduce cyclic fatigue20. Taken together, care should be exercised in the extrapolation of the present results to the clinical situations.

EDM and JZ showed more NCF than PTN and nJZ, which agrees with previous findings that EDM is highly resistant to cyclic fatigue compared with instruments made of different NiTi wires15,16, and indicated that the cyclic fatigue resistance of JZ is comparable to that of EDM. This may be associated with the better flexibility of EDM and JZ compared with PTN and nJZ because flexible instruments are highly resistant to cyclic fatigue18.

This study used simulated resin canals to facilitate a standardized evaluation with direct visual comparison of the centering ratio18,24. However, limitations exist regarding the use of resin canals because of their physical properties such as the relative softness compared with human root dentin30. Moreover, rotary instruments operated in resin canals may become entangled in heat-softened resin and receive larger stresses than those rotated in human root dentin. Further studies using natural teeth are needed to better simulate the clinical condition.

JZ showed better centering ability than nJZ at all measuring points, which is reasonable because more flexible instruments reduce deviated canal preparations31. PTN reportedly shows superior centering ability32 and exhibited similar centering ability to JZ except for 0 mm from the apex. In contrast, EDM showed lower centering ability than PTN and JZ, although EDM is reported to maintain canal curvature similarly to PTN32. This can be explained by the larger taper of EDM (0.08 taper in its apical 4 mm), because larger-tapered instruments produce more degrees of transportation18,33.

The upward force generated during instrumentation represents the screw-in force that can be defined as the force that “pulls” a rotating instrument apically, which may cause instantaneous instrument binding leading to sudden generation of torsional stress24,33,35. In the 1st instrumentation, EDM and JZ exhibited a smaller upward force than the others, which can be attributed to the flexibility of these instruments that reduces internal stresses during instrumentation22. The radial land of JZ may also be associated with the reduction of the screw-in force35. Conversely, the radial land could be associated with the downward force of JZ that was greater than that for EDM during the 2nd instrumentation, as suggested by the finding that ProFile (landed) generates greater downward force than ProTaper (non-landed)30. From clinical viewpoint, care should be exercised in the generation of larger screw-in force during NiTi rotary instrumentation, since it might lead to instrument separation resulting from abrupt increase of torsional load24,33,35. The screw-in force may also cause overinstrumentation beyond the apical foramen, which may induce persisting inflammatory response and postoperative pain or trigger a foreign body reaction27.

In the 2nd instrumentation, JZ and nJZ generated significantly lower torque and upward force than PTN and EDM, which can be attributed, at least in part, to the size and taper of the 1st instrument. In JZ and nJZ, the 2nd instrumentation was done only with increasing taper, in contrast to PTN and EDM where the 2nd instrumentation was carried out with increasing tip size and taper and thus may have led to more torque and force generation. The torque and force generated by JZ were similar in the 1st and 2nd instrumentation. Such uniformity of stress generation over the sequence may contribute to reducing the risk of inadvertent torsional fracture.

Overall, the present results clearly showed superior cyclic fatigue resistance and canal-centering ability of the three heat-treated instruments compared with nJZ, indicating that heat-treated instruments can be recommended to minimize the risk of intracanal file.
separation and apical transportation. However, PTN and EDM generated higher torque and upward force than nJZ particularly in the 2nd instrumentation. Thus, clinicians should be aware that the drawback of the single-length technique, i.e., generation of higher torsional stress than the crown-down technique, cannot always be overcome even by the use of heat-treated instruments.

In conclusion, under the present experimental condition, JZ exhibited flexibility and cyclic fatigue resistance similar to EDM, maintained a canal curvature, and generated smaller torque and screw-in force than PTN and EDM during the 2nd instrumentation in a two-instrument, single-length instrumentation sequence.

ACKNOWLEDGMENTS

The authors thank MANI for supplying NiTi rotary instruments used in the experiment. This study was supported by Research Fund 1B223, Tokyo Medical and Dental University (TMDU).

The authors deny any conflicts of interest related to this study.

REFERENCES

1) Ebihara A, Yahata Y, Miyara K, Nakano K, Hayashi Y, Suda H. Heat treatment of nickel-titanium rotary endodontic instruments: effects on bending properties and shaping abilities. Int Endod J 2011; 44: 843-849.
2) Gambill JM, Alder M, del Rio CE. Comparison of nickel-titanium and stainless steel hand-file instrumentation using computed tomography. J Endod 1996; 22: 369-375.
3) Kyaw Moe MM, Ha JH, Jin MU, Kim YK, Kim SK. Root canal shaping effect of instruments with offset mass of rotation in the mandibular first molar: a micro-computed tomographic study. J Endod 2018; 44: 822-827.
4) Kimura S, Ebihara A, Maki K, Nishijio M, Tokita D, Okiji T. Effect of optimum torque reverse motion on torque and force generation during root canal instrumentation with crown-down and single-length techniques. J Endod 2020; 46: 232-237.
5) Shen Y, Zhou HM, Zheng YF, Feng B, Haapasalo M. Current challenges and concepts of the thermomechanical treatment of nickel-titanium instruments. J Endod 2013; 39: 163-172.
6) Zupanc J, Vahdat-Pajouh N, Schäfer E. New thermomechanically treated NiTi alloys — a review. Int Endod J 2018; 51: 1088-1103.
7) Alapati SB, Brantley WA, Iijima M, Clark WA, Kovarik L, Buie C, et al. Metallurgical characterization of a new nickel-titanium wire for rotary endodontic instruments. J Endod 2009; 35: 1589-1593.
8) Ye J, Gao Y. Metallurgical characterization of M-Wire nickel-titanium shape memory alloy used for endodontic rotary instruments during low-cycle fatigue. J Endod 2012; 38: 105-107.
9) Pereira ES, Gomes RO, Leroy AM, Singh R, Peters OA, Bahia MG, et al. Mechanical behavior of M-Wire and conventional NiTi wire used to manufacture rotary endodontic instruments. Dent Mater 2013; 29: 318-324.
10) Testarelli L, Plotino G, Al-Sudani D, Vincenzi V, Gianciracusa A, Grande NM, et al. Bending properties of a new nickel-titanium alloy with a lower percent by weight of nickel. J Endod 2011; 37: 1293-1295.
11) Pirani C, Iacono F, Generali L, Sassatelli P, Nucci C, Lusvarghi L, et al. HyFlex EDM: superficial features, metallurgical analysis and fatigue resistance of innovative electro discharge machined NiTi rotary instruments. Int Endod J 2016; 49: 483-493.
12) Iacono F, Pirani C, Generali L, Bolelli G, Sassatelli P, Lusvarghi L, et al. Structural analysis of HyFlex EDM instruments. Int Endod J 2017; 50: 303-313.
13) Arias A, Macorra JC, Govindjee S, Peters OA. Correlation between temperature-dependent fatigue resistance and differential scanning calorimetry analysis for 2 contemporary rotary instruments. J Endod 2018; 44: 630-634.
14) Goo HJ, Kwak SW, Ha JH, Pedullè E, Kim HC. Mechanical properties of various heat-treated nickel-titanium rotary instruments. J Endod 2017; 43: 1872-1877.
15) Pedullè E, Lo Savio F, Boninelli S, Plotino G, Grande NM, La Rosa G, et al. Torsional and cyclic fatigue resistance of a new nickel-titanium instrument manufactured by electrical discharge machining. J Endod 2016; 42: 156-159.
16) Palma PD, Messias A, Cerqueira AR, Tavares LD, Caramelo F, Roseiro L, et al. Cyclic fatigue resistance of three rotary file systems in a dynamic model after immersion in sodium hypochlorite. Odontology 2018; 324: 332.
17) Miyara K, Yahata Y, Hayashi Y, Tsutsu Y, Ebihara A, Hanawa T, et al. The influence of heat treatment on the mechanical properties of Ni-Ti file materials. Dent Mater J 2014; 33: 27-31.
18) Fukumori Y, Nishijio M, Tokita D, Miyara K, Ebihara A, Okiji T. Comparative analysis of mechanical properties of differently tapered nickel-titanium endodontic rotary instruments. Dent Mater J 2018; 37: 667-674.
19) Pruett JP CD, Carnes DL Jr. Cyclic fatigue testing of nickel-titanium endodontic instruments. J Endod 1997; 23: 77-85.
20) Tokita D, Ebihara A, Nishijio M, Miyara K, Okiji T. Dynamic torque and vertical force analysis during nickel-titanium rotary root canal preparation with different modes of reciprocal rotation. J Endod 2017; 43: 1706-1710.
21) Maki K, Ebihara A, Kimura S, Nishijio M, Tokita D, Okiji T. Effect of different speeds of up-and-down motion on canal centering ability and vertical force and torque generation of nickel-titanium rotary instruments. J Endod 2019; 45: 68-72.
22) Gagliardi J, Versiani MA, de Sousa-Neto MD, Plazas-Garzon A, Basrani B. Evaluation of the shaping characteristics of ProTaper Gold, ProTaper NEXT, and ProTaper Universal in curved canals. J Endod 2015; 41: 1718-1724.
23) Uygun AD, Koç E, Topcu MK, Seckin F, Ersoy I, Tanriver M. Variations in cyclic fatigue resistance among ProTaper Gold, ProTaper Next and ProTaper Universal instruments at different levels. Int Endod J 2018; 49: 494-499.
24) Maki K, Ebihara A, Kimura S, Nishijio M, Tokita D, Miyara K, et al. Enhanced root canal-centering ability and reduced screw-in force generation of reciprocating nickel-titanium instruments with a post-machining thermal treatment. Dent Mater J 2020; 39: 251-255.
25) Yahata Y, Yoneyama T, Hayashi Y, Ebihara A, Doi H, Hanawa T, et al. Effect of heat treatment on transformation temperatures and bending properties of nickel-titanium endodontic instruments. J Endod 2014; 40: 621-626.
26) Xu X, Eng M, Zheng Y, Eng D. Comparative study of torsional and bending properties for six models of nickel-titanium root canal instruments with different cross-sections. J Endod 2006; 32: 372-375.
27) Versluis A, Kim HC, Lee W, Kim BM, Lee CJ. Flexural stiffness and stresses in nickel-titanium rotary file for various pitch and cross-sectional geometries. J Endod 2012; 38: 1399-1403.
28) Li UM, Lee BS, Shih CT, Lan WH, Lin CP. Cyclic fatigue of endodontic nickel titanium rotary instruments: static and dynamic tests. J Endod 2002; 28: 448-451.
30) Weine FS, Kelly RF, Lio PJ. The effect of preparation procedures on original canal shape and on apical foramen shape. J Endod 1975; 1: 255-262.
31) Pinheiro SR, Alcalde MP, Vivacqua-Gomes N, Bramante CM, Vivian RR, Duarte MAH, et al. Evaluation of apical transportation and centering ability of five thermally treated NiTi rotary systems. Int Endod J 2018; 51: 705-713.
32) Venino PM, Citterio CL, Pellegatta A, Ciccarelli M, Maddalone M. A micro-computed tomography evaluation of the shaping ability of two nickel-titanium instruments, HyFlex EDM and ProTaper Next. J Endod 2017; 43: 628-632.
33) Bürklein S, Poschmann T, Schäfer E. Shaping ability of different nickel-titanium systems in simulated S-shaped canals with and without glide path. J Endod 2014; 40: 1231-1234.
34) Ha JH, Jin MU, Kim YK, Kim SK. Comparison of screw-in effect for several nickel-titanium rotary instruments in simulated resin root canal. J Korean Acad Conserv Dent 2010; 35: 267-272.
35) Ha JH, Cheung GSP, Versluis A, Lee CJ, Kwak SW, Kim HC. ‘Screw-in’ tendency of rotary nickel-titanium files due to design geometry. Int Endod J 2015; 48: 666-672.
36) Peters OA, Boessler C, Zehnder M. Effect of liquid and paste-type lubricants on torque values during simulated rotary root canal instrumentation. Int Endod J 2005; 38: 223-239.
37) Siqueira JF Jr. Microbial causes of endodontic flare-ups. Int Endod J 2003; 36: 453-463.