Enhanced root canal-centering ability and reduced screw-in force generation of reciprocating nickel-titanium instruments with a post-machining thermal treatment

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This study aimed to evaluate the influence of a post-machining thermal treatment on canal-centering ability and torque/force generation of reciprocating nickel-titanium instruments. Simulated J-shaped resin canals were prepared with reciprocating instruments sharing identical geometric architecture and with/without post-machining thermal treatment (Reciproc Blue/Reciproc, VDW, Munich, Germany). Using an original automated root canal instrumentation and torque/force analyzing device, files were operated in a combination of reciprocation and up-and-down motion, and torque/force values were monitored. Canal-centering ratios were measured after superimposition of pre- and post-instrumentation images. Compared with Reciproc, Reciproc Blue showed a significantly lower canal-centering ratio (i.e., less deviation; \( p<0.05 \)) at 0–1 mm from the apex and generated a significantly smaller upward maximum vertical force (\( p<0.05 \)). Under standardized conditions using the automated device, Reciproc Blue showed better canal-centering ability and reduced screw-in forces than Reciproc, indicating that the post-machining thermal treatment confers superior performance to reciprocating nickel-titanium instruments.

Keywords: Nickel-titanium rotary instrument, Centering ability, Screw-in force, Thermal treatment, Torque

INTRODUCTION

Nickel-titanium (NiTi) rotary instruments are widely used in root canal treatment because of their superior flexibility and better cutting efficiency compared with stainless steel files\(^{1,2}\). However, separation of instruments and creation of iatrogenic irregularities are still matters of concern, particularly during instrumentation of narrow and curved canals. To prevent such mishaps, NiTi rotary instrument systems have been upgraded by adopting various new technologies such as reciprocating motion\(^{3,4}\) and thermal treatment of NiTi alloys\(^{5}\).

Thermal treatment of NiTi alloys has been widely adopted to enhance the flexibility and cyclic and torsional fatigue resistance\(^{5,9}\). NiTi alloy is usually thermal treated at 450 to 550ºC to obtain superelastic and shaping memory properties\(^{8,9}\). The thermal treatment changes the phase transformation temperature of the NiTi alloy, leading to the appearance of the martensite phase and/or the R-phase, which are soft and ductile and can be easily deformed at body temperature\(^{6,9}\).

A reduction in the number of instruments simplifies root canal instrumentation\(^{9}\). The single file reciprocating system, in which only one NiTi instrument is used with reciprocating motion throughout root canal preparation, has gained popularity. The reciprocating motion is based on the balanced force technique for manual instrumentation and can be described as motion in which an instrument rotates in one direction and then reverses the direction before completing 360º of rotation\(^{10,12}\). Instruments used with reciprocating motion show better resistance to cyclic fatigue and induce less canal transportation than those used with continuous rotation\(^{12}\).

Reciproc (VDW, Munich, Germany) is one of the single file reciprocating systems that initially appeared on the market, and is manufactured after a pre-machining thermal treatment of blank NiTi alloy wire. This type of thermal-treated wire contains certain amounts of martensite at body temperature\(^{13}\), and shows improved cyclic fatigue resistance and flexibility compared with conventionally processed NiTi wires\(^{4}\). Reciproc has an S-shaped cross section, two cutting edges, and a noncutting tip that perform reciprocating motion, and is powered by specific motors equipped with a preset program called the “Reciproc All” mode (150º counterclockwise and 30º clockwise rotation at a speed of 300 rpm).

Reciproc has recently been updated to Reciproc Blue (VDW), which shares identical size, cross-sectional design and geometry with Reciproc, but is manufactured with a new thermal treatment, which is a post-machining treatment and gives the instrument blue color. Due to the thermal treatment, the NiTi alloy used in Reciproc Blue is assumed to contain a greater amount of stable martensite than the NiTi alloy used in Reciproc\(^{8}\). Moreover, the thermal-treated alloy used in Reciproc Blue shows a two-stage martensitic transformation with the occurrence of R-phase\(^{15}\), which is an intermediate phase formed during the austenite-martensite phase transformation and shows high cyclic fatigue resistance\(^{6}\). Improved flexibility\(^{16}\) and cyclic fatigue resistance\(^{16,18}\) have actually been reported for Reciproc Blue compared with Reciproc.
To our knowledge, no study has been performed to compare the shaping ability and stress generation of Reciproc Blue versus Reciproc. Therefore, this study was performed to evaluate the canal-centering ability and torque/force generation of these instruments using an automated root canal instrumentation and torque/force measuring device\textsuperscript{19}. The null hypothesis was that there are no differences in the centering ability and stress generation between Reciproc Blue and Reciproc.

MATERIALS AND METHODS

Automated root canal instrumentation and torque/force analyzing device
An original device described in our previous articles\textsuperscript{19-22} was used with a few modifications. The device consists of an endodontic motor (X-Smart Plus, Dentsply Sirona, Ballaigues, Switzerland), a motorized test stand (MX2-500N, Imada, Aichi, Japan), and a torque/force measuring unit. The handpiece of the motor is attached to the moving stage of the test stand using a custom-made holder. In the present study, the handpiece was programmed to move downward for 2 s and upward for 1 s regardless of the stress applied. A metal stage, on which a canal model was fixed, was connected to the torque/force measuring unit, which consisted of a torque sensor (LUX-B-ID, Kyowa Electronic Instruments, Tokyo, Japan) to measure vertical force and strain gauges (KFG-2-120-D31-11, Kyowa Electronic Instruments) to measure torque.

Root canal instrumentation
Fourteen simulated resin canal blocks with a J-shaped canal (Endo Training Bloc, 0.02 taper, 17 mm length, 45° curvature, Dentsply Sirona, Fig. 1) were used in this study. The working length was set on the apex of the simulated resin blocks. The blocks were randomly divided into two experimental groups (n=7 each) for instrumentation with Reciproc Blue R25 or Reciproc R25 (size 25, 0.08 taper at the tip; 25 mm). Each block was fixed on the metal stage of the automated root canal instrumentation device through an acrylic tube with three screws. The canals were instrumented with Reciproc Blue or Reciproc attached to the handpiece of the device, and the instruments were rotated using the “Reciproc All” mode and moved axially with a simulated pecking motion; i.e., 2 s downward and 1 s upward at a speed of 10 mm/min. The coronal portion of the canals were firstly instrumented to 6 mm from the apex, followed by instrumentation in 2 mm increments until the working length was reached. After each instrument use, the canals were irrigated with 1 mL of distilled water and the canal patency was manually checked with a #10 stainless steel K-file (Zipperer, Munich, Germany). During the instrumentation, the canals were filled with RC-Prep™ (Premier Dental, Plymouth Meeting, PA, USA) as a lubricant. Each NiTi instrument was used in one canal only. When instrument fracture or ledge formation occurred, the block was excluded from further analysis.

Measurement of canal-centering ratio
The canal-centering ratio was determined using image analyzing software (Photoshop 7.0, Adobe Systems, San Jose, CA, USA), according to our previous study\textsuperscript{22} (Fig. 1). Briefly, images before and after instrumentation were taken with a digital microscope (VH-8000, Keyence, Osaka, Japan) at ×20 magnification, and iatrogenic irregularities were checked. Following superimposition of the two images, four concentric circles (0.5, 1, 2, and 3 mm radius) centering the apex of the pre-instrumentation canal were determined as the points at which the reference line intersected the inner and outer outlines of the pre- and post-instrumentation canals. X and Y represent the amount of resin removed from the inner and outer walls, respectively, and Z represents the post-instrumentation canal diameter.

Fig. 1 Representative superimposed images showing the method used to measure the amount of resin removal.
(a) A reference point (black point) was determined as the intersection point of the pre-instrumentation canal axis and a circle (0.5, 1, 2, or 3 mm in diameter) centering the apex of the pre-instrumentation canal. A reference line passing through the reference point and perpendicular to the canal axis (black line) was drawn. (b) Four measuring points (white points) were determined as the points at which the reference line intersected the inner and outer outlines of the pre- and post-instrumentation canals. X and Y represent the amount of resin removed from the inner and outer walls, respectively, and Z represents the post-instrumentation canal diameter.
corresponding measuring points on the reference line (Fig. 1b). The centering ratio was calculated by the following formula: 
\[
(\text{amount of resin removed from the outer side}) - (\text{amount of resin removed from the inner side}) / (\text{post-instrumentation canal diameter})
\]
Using this formula, a value of 0 indicates perfect centering, and positive and negative values indicate transportation to the outer and inner side, respectively.

**Torque/force measurement**

During instrumentation with Reciproc Blue or Reciproc, the torque and vertical force were measured with the torque/force measuring unit described above. Torque in the cutting and noncutting directions on the block was defined as counterclockwise and clockwise torque, respectively, and apically directed and opposite vertical forces on the block were defined as downward and upward vertical forces, respectively. The mean values of the maximum counterclockwise (cutting direction) and clockwise (noncutting direction) torque and downward and upward vertical force generated during instrumentation were evaluated.

**Postoperative examination of rotary instruments**

All Reciproc Blue and Reciproc instruments used for instrumentation were examined with a surgical operating microscope (OPMI pico, Carl Zeiss, Gottingen, Germany) at ×21.3 magnification for any possible defect or distortion (plastic deformation). The number of fractured and distorted instruments was recorded.

**Statistical analysis**

Two-way analysis of variance (ANOVA) and the Tukey test were used to compare the canal-centering ratio of the 2 groups at 0, 0.5, 1, 2, and 3 mm from the apex. The unpaired t test was used to compare the mean maximum torque and vertical force. A p-value of <0.05 was considered statistically significant.

**RESULTS**

**Canal-centering ratio**

Figure 2 shows the mean centering ratio of Reciproc Blue and Reciproc. Two-way ANOVA showed that two factors, “instruments” and “measuring points”, influenced the centering ratio (p<0.05). There were significant interactive effects between the two factors (p<0.05). At 0, 0.5, and 1 mm from the apex, Reciproc Blue showed a significantly lower centering ratio (i.e., less deviation) than Reciproc (p<0.05). At 2 and 3 mm from the apex, there was no significant difference (p>0.05). In Reciproc, centering ratio at 3 mm from the apex was significantly lower than that at 0, 0.5, 1 and 2 mm (p<0.05). In Reciproc Blue, however, there was no significant difference in centering ratio among different measuring points (p>0.05).

A ledge was formed in one canal during instrumentation with Reciproc, whereas no ledge formation occurred with Reciproc Blue.

**Torque and vertical force**

Table 1 shows the mean values of the maximum counterclockwise and clockwise torque and downward and upward vertical force. Reciproc Blue showed significantly smaller upward vertical force, representing the screw-in force, than Reciproc (p<0.05). There were no significant differences in the maximum downward vertical force (p>0.05). There was no significant difference in the maximum torque of each direction (p>0.05).

| Instruments | Torque (N-mm) | Vertical force (N) |
|-------------|--------------|--------------------|
|             | Counterclockwise | Clockwise | Downward | Upward |
| Reciproc Blue | 26.80 (3.82)a | 4.99 (2.24)b | 2.96 (0.95)a | 9.84 (0.91)b |
| Reciproc     | 29.06 (3.71)a  | 6.51 (2.69)b      | 3.72 (0.57)a | 11.21 (1.15)b |

Means with the different superscript letter in each column are significantly different (p<0.05, unpaired t-test).
Incidence of file fracture/distortion
No file fracture or distortion occurred in either Reciproc Blue or Reciproc.

DISCUSSION
To our knowledge, this study is the first to compare the canal-centering ability and stress generation of Reciproc Blue versus Reciproc during instrumentation of curved canals. The comparison was standardized by use of an automated root canal instrumentation and torque/force analyzing device. The null hypothesis was partially rejected because Reciproc Blue exhibited a better centering ratio and lower maximum upward vertical force than Reciproc.

Reciproc Blue is characterized by a proprietary metallurgy obtained through the post-machining thermal treatment, which generates a blue titanium oxide layer on the surface of the instrument. Given that Reciproc Blue and Reciproc instruments share identical size, design, geometry and operational mode, our findings may be solely explained by the different thermal treatment and resulting metallurgical differences, e.g., bending behaviors and the pattern of stress and strain distribution, between the two instruments. In particular, Reciproc Blue shows lower bending resistance and microhardness than Reciproc, which is most probably attributed to the higher cyclic fatigue resistance of Reciproc Blue than that of Reciproc.

The alloy used in Reciproc Blue is assumed to contain martensite and R-phase at the body temperature, and such phase composition may contribute to the improved flexibility and cyclic fatigue resistance of Reciproc Blue compared with Reciproc. Reciproc Blue also shows higher cyclic fatigue resistance than WaveOne Gold (Dentsply Sirona), which is another single file reciprocating instrument produced with a post-machining thermal treatment.

In the present study, simulated resin canal blocks were used to allow standardized evaluation because the influence of anatomical variation of real teeth could be excluded. However, limitation exists regarding the use of simulated resin canals because the physical properties of these simulated canals, such as hardness, differ from those of real teeth.

During instrumentation, preservation of the original shape and curvature of the root canal system is of utmost importance to achieving a favorable outcome of root canal treatment. In this study, both Reciproc Blue and Reciproc created apical transportation to the outer side, which can be explained by the fact that NiTi instruments have the tendency to restore their original linear shape during instrumentation of curved root canals. Reciproc Blue showed better canal-centering ability than Reciproc at 0, 0.5, and 1 mm from the apex (Fig. 2), which can be explained by the superior flexibility of Reciproc Blue and method used to evaluate the shaping ability (microscopy vs. micro-computed tomography).

Reciproc has been shown to generate larger screw-in force than several other NiTi instruments. The “screw-in effect” can be defined as the tendency of a rotary file to be “pulled” into the canal by an apical driving force produced through the engagement of spirally configured blades in the canal wall dentin during rotation. An upward vertical force acting on a canal model represents generation of the screw-in force. The “screw-in force” may cause over instrumentation beyond the apical foramen if not adequately resisted. It may also lead to instantaneous binding of a file, which increases the risk of instrument separation due to abrupt torsional stress. The cross sectional shape, pitch length, motion (continuous rotation or reciprocation), and thermal treatment reportedly influence the degree of the screw-in effect.

In the present study, Reciproc Blue showed significantly lower upward force (acted on the block) than Reciproc (Table 1), indicating that the employment of the post-machining thermal treatment is responsible to the generation of lower screw-in force. The superior flexibility of Reciproc Blue compared with Reciproc may be attributed to the lower screw-in force, through the reduction of excessive internal stress generated during instrumentation.

CONCLUSION
Under standardized conditions using the automated instrumentation and torque/force analyzing device, Reciproc Blue showed better canal-centering ability and reduced screw-in forces when compared with Reciproc, indicating that the post-machining thermal treatment applied to Reciproc Blue confers superior performance to reciprocating NiTi instruments.

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