Influence of Cross-sectional Design and Dimension on Mechanical Behavior of Nickel-Titanium Instruments under Torsion and Bending: A Numerical Analysis

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Abstract

Introduction: The aim of this study was to examine the influence of the cross-sectional configuration and dimensions (size and taper) on the torsional and bending behavior of nickel-titanium rotary instruments, taking into account the nonlinear mechanical properties of material. Methods: Ten cross-sectional configurations, square, triangular, U-type, S-type (large and small), convex-triangle, and 4 proprietary ones (Mani NRT and RT2, Quantec, and Mtwo), were analyzed under torsion or bending by using a 3-dimensional finite element method. The von Mises stresses were correlated with the critical values for various phases of the nickel-titanium material. Results: Different loading conditions led to unequal patterns of stress distribution. Increasing the applied torque or bending angle resulted in a rise in the corresponding stresses in the instrument. Favorable stress distribution without dangerous stress concentration was observed if the material was undergoing superelastic transformation at that applied load. The ultimate strength of the material was not exceeded when the instrument was bent up to a 50-degree curvature. On the other hand, a torsional moment of greater than 1.0 N·mm was applied, the maximum stresses developed in some designs would exceed the ultimate strength of the material. Little variation in the von Mises stresses was observed for instruments of different nominal sizes and tapers on bending to similar extent. Conclusions: The cross-sectional design has a greater impact than taper or size of the instrument on the stresses developed in the instrument under either torsion or bending. Certain cross-sectional configurations are prone to fracture by excess torsional stresses. (J Endod 2010;36:1394–1398)

Key Words

Finite element analysis, nickel-titanium, root canal instrument, rotary files, superelastic, three-dimensional model

Materials and Methods

Finite element models were constructed for instruments of 10 distinctly different cross-sectional designs by expressing all boundary conditions and geometric configuration numerically (Fig. 1). The cross-sectional configuration (for several brands) was obtained by serial grinding of an embedded instrument and capturing the shape with an image measuring device (VCAD-1010; HLEO, Beijing, China). Then an idealized shape was established in CAD software (SolidWorks; Dassault Systemes, Velizy-Villacoublay, France). A smart sweep meshing method, which was optimized with sufficient number of elements with acceptable calculation time, was used to best-fit a mesh on each instrument in FEA software (ANSYS, Canonsburg, PA); the number of nodes might not be the same for all designs of instrument. Data were entered into the software package (ANSYS), together with the nonlinear mechanical properties of the NiTi material. Critical values for the start and end point of SIM transformation and the ultimate strength of the material were obtained from published data for SE508 alloy from which NiTi rotary files are made (9, 10). Multilinear interpolation was made to estimate the
intermediate values for the different phases of NiTi material (Table 1). A stress value exceeding 1400 MPa (the ultimate tensile strength of NiTi) was deemed to result in breakage of the instrument.

Two modes of loading were simulated. Either a torsional or bending moment was applied to the tip of instrument, with the other end (shank) fixed. For the torsional analysis, different torque values (0.25, 0.5, 1.0, 1.5, and 2.0 N·mm) were applied to the 10 cross-sectional configurations at their tip. The radius of the circle circumscribing each cross section was fixed at 0.15 mm (ie, size 30). For the bending analysis, all groups (simulated size 30, with a 0.04 taper) were curved to a maximum of 50 degrees at 10-degree intervals, with the length of the curved (arc) portion confined to 10 mm (Fig. 1B). The degree of curvature was determined by controlling the tip displacement, akin to the method described by Schneider (11). The bending test was repeated with instruments of a different size or taper.

Results

Fig. 2 depicts the distribution of von Mises stresses in the torsion test; the (pseudo)colors corresponded to the range of stress values on a nonlinear scale (Table 1), corresponding to the transformation between phases of the NiTi material. Generally, the maximum stress occurred at the periphery (or border) of the cross section and often was located near the base or “bottom” of the flute. When the applied torque was small (0.25 or 0.5 N·mm), most instruments were still in their austenitic phase, ie, within the linear elastic range of the austenitic material (blue and cyan regions in Fig. 2). As the torsional moment increased to 1.0 N·mm, there was only a small rise in this maximum reaction stress for the NRT, both dimensions of S-type, Mtwo, convex-triangular, and the square cross section, indicating that these instruments were within their superelastic range, that is, the material was transforming with both austenite and stress-induced martensite being present (green region in Fig. 2). For the U-type, Quantec, RT2, and the triangular cross section, the maximum stress developed was greater than 1200 MPa, which indicated that these instruments had gone beyond the superelastic plateau stage. No obvious stress concentration (ie, spotty areas with high stresses) was observed for some but present in other configurations (Fig. 2). Increasing the torsional moment (to 1.5 N·mm or higher) led to increasing amount of stress-induced martensitic phase, followed by elastic and then plastic deformation of the martensite; high von Mises stresses were observed. Breakage was anticipated for some designs: U-type triangular (1.5 N·mm), Quantec (1.5 N·mm), Mtwo (2.0 N·mm), and RT2 (2.0 N·mm) (Fig. 2). Convex-triangle and the (large) S-type showed the highest resistance (with a lower stress value and with a more even stress distribution) to torsional failure among the 10 cross-sectional configurations (Fig. 2). The U-type Quantec and triangular cross section showed the greatest susceptibility to torsional failure, according to the maximum stress values that would develop in the instrument (Fig. 3A).

In the case of bending, there existed a neutral plane where the stress was approximately zero (blue region in Fig. 1B), which was color-coded according to values in Table 1. The maximum stresses occurred on the surface of the instrument at a site furthest away from this neutral plane. There was no significant stress concentration in the flute for all cross sections examined. When the angle of curvature

| Phase                  | Stress (MPa) | Strain (%) | Stage                                      | Color coding*
|------------------------|--------------|------------|--------------------------------------------|----------------
| Austenite phase (A)    | 0–160        | 0–0.8      | Linear elasticity                          | Blue           |
|                        | 160–320      | 0.8–1.4    |                                             | Sky-blue       |
|                        | 320–480      | 1.4–2.1    | Supерelasticity (stress-induced martensitic transformation) | Cyan           |
| Transformation phase (A + M) | 480–530     | 2.1–6.3    |                                             | Green          |
|                        | 530–580      | 6.3–7.7    | End of SIM transformation, and elastic range of the martensite | Kelly          |
| Martensitic phase (M)  | 760–1160     | 7.7–9.8    | Plastic deforation of martensite           | Yellow         |
|                        | 1160–1400    | 9.8–12.6   |                                             | Red            |

*Pseudocolors applied to the stress contour map in FEA models.
Figure 2. Contour map showing the distribution of von Mises stresses for 10 instruments of different cross sections, with each (pseudo)color corresponding to the stress range described in Table 1. (This figure is available in color online at www.aae.org/joe/.)
was increased, the stress value rose rapidly at first. The rate of increase in stress then slowed down at curvatures between 20 and 40 degrees, before it rose again on further bending (Fig. 3B). At a curvature of 50 degrees, several instruments (Quantec, NRT, Mtwo, RT2, and ProFile in that order) demonstrated a much higher stress than the others (Fig. 3B). When the taper or size of the instrument was altered, little influence on the maximum stress developed for various amounts of bending was observed. The maximum von Mises stress increased slightly when the instrument size and taper increased (Fig. 3C, D), with the area undergoing SIM transformation increased in size (green region in Fig. 1B). The superelastic property of the material appeared to have maintained the stress within a safe range on bending; no significant difference in the von Mises stresses for the various cross-sectional configurations could be found for instruments of the same size but different tapers (Fig. 3C) or of the same taper but different sizes (Fig. 3D).

### Discussion

The force acting on the endodontic files in use might be resolved into 2 components, torsion and bending. It has been suggested than the load-deflection behavior for combined torsion and bending might be resolved into these 2 pure modes for analysis (12). Results from the present numerical analysis indicated that the NiTi instrument is more likely to succumb to (a single application of) excess torsion than excess bending. For instance, a curvature of 50 degrees would only give rise to a stress of about 700–800 MPa on the outermost fibers of the instrument, which value is just into the martensitic phase but much lower than the material’s ultimate tensile strength (1400 MPa). However, a torsional moment greater than 1.0 N•mm would cause some instruments of certain designs to develop local stresses to a rather high level. Torque of this value might easily be attained if the endodontic file is "locked" during canal preparation. In other words, the excess torsion is more "dangerous" than bending moment (although repeated bending would undoubtedly lead to fatigue breakage). That justifies the use of torque-controlled motors to avoid shear fracture of the rotary instruments, especially for some vulnerable designs. The result also indicates that rotary instruments seldom fail as a result of a single episode of excessive bending (ie, in canal with a small radius of curvature) but rather as a result of fatigue failure. Even if the instrument might be loaded to beyond the SIM transformation, that bending stress is insufficient to cause immediate fracture (Fig. 3B). Continuous rotation, however, will lead to failure due to low-cycle fatigue (3, 13), with the periphery of the instrument strained well into and sometimes beyond the superelastic range in the curved canal.

U-file, Quantec, and file of a triangular cross section showed the least resistance to torsional breakage than the other instruments examined. Indeed, 2 commercial products both of a triangular cross section have been shown to be less resistant to repeated torsional loads, compared with those of a convex-triangular cross section (14). This might be related to the deep flutes cut into these cross sections, resulting in a small inner core diameter (15). Because the principle of mechanics dictates that the stress at any point in a structure is inversely proportional to its radial distance to the centroid of the cross section (16), any instrument with a small core diameter would be prone to torsional overload, an observation that was noted for NiTi rotary instruments that were discarded after clinical use (16). It seems that instruments of a cross-sectional design that distributes the torsional stress well would be most suited for use in constricted canals, in which situation a high reaction stress in the material is likely (2). Those possessing high flexibility with relatively low reaction stresses on bending would be more suitable for preparing the more severely curved canals, on the basis of mechanical considerations. In the clinical situation, the cutting efficiency of the design would also be a consideration.
It is widely accepted that instruments of a smaller diameter are able to withstand a higher number of cycles of flexural fatigue loading (rotational bending) than those larger instruments of the same design (17–19). However, the dimensions (tip size or taper) seem to have little effect on the maximum von Mises stress when instrument was bent to a similar angle (eg, 30 degrees) of curvature; only a small effect on the maximum reaction stresses could be noticed. The material apparently was deforming within its superelastic range. Thus, the stress value stayed at about the SIM transformation threshold, despite the increased amount of deformation (strain) for those files of somewhat larger size or taper. Obviously, if one were to examine the fatigue behavior of NiTi rotary files, the surface strain should be considered rather than the stress value for the low-cycle fatigue behavior (3, 13). When the maximum stress developed in the material was also found to differ significantly for different cross-sectional designs in a curved root canal, the stresses developed in the instrument. In other FEA studies that simulated the use of NiTi instruments, our results indicated that the cross-sectional configuration is the main determinant of the stresses developed in the material is concerned, our results indicated that the cross-sectional configuration is the main determinant of the stresses developed in the instrument. In other FEA studies that simulated the use of NiTi instruments of various designs in a curved root canal, the stresses developed in the material were also found to differ significantly for different cross-sectional configurations (20, 21). This is probably due to the fact that stress concentration is governed by the geometry of the part rather than the material property (16). It is alarming that some instruments that developed high von Mises stresses on bending (Quartec, NRT, and MTtwo; Fig. 3B) were also susceptible to torsional failure. This underlines the importance of design on durability and safety of an instrument. In summary, from this numerical analysis, it might be concluded that certain cross-sectional configurations are more prone to failure by torsional overload than others. The cross-sectional design of the instrument has a significant impact on the bending stresses developed in the NiTi rotary instrument, more so than the size and taper.

References