

Comparison of Forces Generated During Root Canal Shaping and Residual Stresses of Three Nickel–Titanium Rotary Files by Using a Three-Dimensional Finite-element Analysis

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Abstract

The study was aimed to compare the stress distribution during simulated root canal shaping and to estimate the residual stress thereafter for some nickel-titanium rotary instruments. Three brands of instruments (ProFile, ProTaper, and ProTaper Universal; Dentsply Maillefer) were scanned with micro-computed tomography to produce a real-size, 3-dimensional model for each. The stresses on the instrument during simulated shaping of a root canal were analyzed numerically by using a 3-dimensional finite-element package, taking into account the nonlinear mechanical behavior of the nickel-titanium material. From the simulation, the original ProTaper design showed the greatest pull in the apical direction and the highest reaction torque from the root canal wall, whereas ProFile showed the least. In ProTaper, stresses were concentrated at the cutting edge, and the residual stress reached a level close to the critical stress for phase transformation of the material. The residual stress was highest in ProTaper followed by ProTaper Universal and ProFile. (*J Endod* 2008;34:743–747)

Key Words

Finite element analysis, NiTi rotary files, residual stresses, screwing, stress distribution

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The objective of the root canal preparation is to clean and shape the root canal space without creating any iatrogenic aberrant forms such as ledge, canal transportation, or perforation (1). Broken instrument is also an unpleasant event in the clinical situation. Root canal instruments manufactured from nickel-titanium (NiTi) alloy were introduced in 1988 to overcome the rigidity (high modulus of elasticity) of stainless steel material (2). The superelasticity of the material allows the NiTi rotary instruments to be used in continuous rotation, even in curved root canals, to produce a desirable, tapered root canal form, with a low risk of transporting the original canal lumen (3–6). However, there is a general perception that NiTi instruments have a high risk of fracture in use.

Various brands of NiTi rotary system have been introduced to the market, each having a slightly different design for its cross-sectional shape, helical angle, and “radial lands” (if any) (6–8). Most of them come with a regularly tapered shaft, whereas some (ProTaper and ProTaper Universal; Dentsply Maillefer, Ballaigues, Switzerland) have a varying taper along the length of the instrument (9). The ProFile Rotary Instrument (Dentsply Maillefer) is one of the earliest NiTi systems introduced; it possesses 3 U-shaped flutes in cross section with 3 radially symmetrical “land” areas (Fig. 1A). The ProTaper system has a cross-sectional design of a triangle with convex sides (Fig. 1B). Its pointed cutting edge (ie, vortex of the triangle in cross section) is claimed to reduce the contact area between the file and the canal wall, hence a good cutting efficiency (10). The original ProTaper instrument has been said to transport canals slightly more than other NiTi systems in extracted human teeth (11) and in resin blocks (12). The ProTaper Universal was launched recently as an improvement to the original design. It incorporates a shallow U-shaped groove at each of its convex triangular sides in cross section (Fig. 1C), supposedly to improve the flexibility of the larger instruments. The modified design has also been suggested to reduce the subjective feeling of the instrument being “pulled” into the canal or so-called screw-in effect (9, 10). Such tendency of pulling in an apical direction has been experienced with many NiTi engine-files, but it seldom occurs with hand instruments.

Separation of rotary NiTi instrument in the root canal has been a matter of concern for many clinicians. An instrument might fracture at various levels of stress or strain, with or without any apparent signs of plastic deformation adjacent to the fracture site (13–15). Two mechanisms of fracture have been proposed, torsional (shear) and flexural (fatigue) (13, 16). The design of the instrument has been suggested to affect its mechanical behavior (7, 8), hence the tendency to fracture. To date, there has been no report of the presence of residual stress in the instrument after use. Residual stresses might be induced in a part after mechanical loading, which stresses could jeopardize the durability of the part if it is to be loaded repeatedly. The purposes of this study were to compare the screw-in tendency of 3 NiTi instruments under simulated root canal shaping and to estimate the residual stress after such simulated use by mathematically using a 3-dimensional (3D) finite-element (FE) analysis.

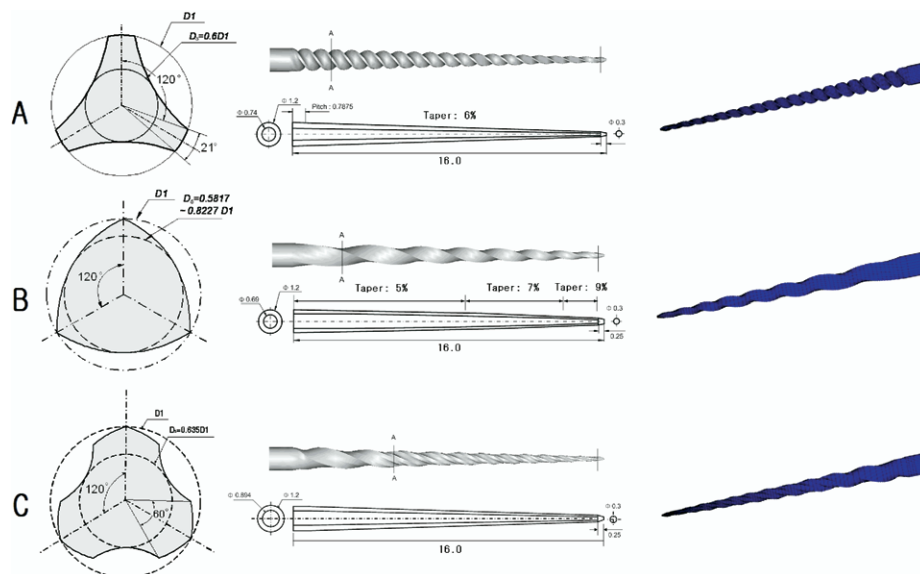


Figure 1. Schematic drawings of the cross-sectional (left column) and longitudinal shapes (center column) of the 3 NiTi instruments examined: (A) ProFile size 30, 0.06 taper; (B) ProTaper F3; and (C) ProTaper Universal F3. The final 3D model for each is shown in the right-most column (right).

Materials and Methods

Constructing a 3D-FE Model

Three brands of NiTi instruments, ProFile (size 30, 0.06 taper), ProTaper F3, and ProTaper Universal F3 (all from Dentsply Maillefer), were scanned at 2- μ m interval in a micro-computed tomography machine (HMX; X-Tek Group, Santa Clara, CA) to obtain a real-size, geometric configuration of the instrument in 3 dimensions. The noise in the 3D stack of data was suppressed digitally, and a 3D model of each instrument (Fig. 1) was reproduced in software (IDEAS11 NX; UGS, Plano, TX).

A mesh of linear, 8-noded, hexahedral elements was laid over the instrument in software to produce a 3D model for entry into FE analysis. The final model for ProFile consisted of 11,880 elements with 16,318 nodes, for ProTaper 7,560 elements with 9,017 nodes, and for ProTaper Universal 8,964 elements with 10,668 nodes (Fig. 1). The z-axis was chosen to be normal to the cross section, ie, along the length of the instrument.

Mechanical Property of NiTi Material

The nonlinear mechanical behavior of NiTi material, similar to the one reported by others (17), was taken into account in this study. Briefly, the model stress-strain behavior of NiTi alloy comprises a linear elastic deformation of the parent phase (austenite), a pseudoelastic plateau during which stress-induced phase transformation from austenite to martensite occurs, followed by elastic and then plastic deformation of the martensitic phase. The elastic strains (of both the austenite and martensite) and the transformation strain are mostly reversible, but the plastic strain is not (17, 18). The general mechanical properties entered for the NiTi material in the analysis were Young's modulus = 36 gigapascals (GPa) and the Poisson's ratio = 0.3. The critical stress at the beginning of the forward phase transformation was taken as 504 megapascals (MPa) and at the end point of recoverable strain was 755 MPa (18).

Mathematical Simulation of Root Canal Shaping

Another 3D-FE model was constructed for a root canal 13 mm long with a curvature of 45-degree angle and 6-mm radius. The model canal had an apical foramen of 0.50-mm diameter and about 5% apical taper.

The behavior of the 3 brands of NiTi file was analyzed numerically in an FE package (ABAQUS V6.5-1; SIMULIA, Providence, RI) to simulate the bending and torsional conditions during root canal shaping. The file was inserted to the full length of the simulated root canal (Fig. 2A), and the stress distribution on the surface and within the instrument was evaluated. The virtual rotation rate was 240 rpm for all instruments. The screw-in tendency, measured as the force acting on the file in an apical direction, was recorded. The residual stress in the instrument after removal from the canal and completion of elastic recovery was also examined.

Results

During insertion into the canal, all files experienced a force, but to varying degrees, along the direction of its longitudinal axis, pulling it apically (Fig. 2B), as well as a reaction torque from root canal wall (Fig. 2C). The value of the force became more or less constant (with slight fluctuations) once the full length of the canal was reached. The ProTaper instrument showed the highest value for both, whereas ProFile showed the lowest.

The distribution of stresses over and within the instrument rotating at the working length is depicted in Fig. 3. Stresses were concentrated at the cutting edge of the original ProTaper, whereas the highest stress was situated adjacent to (but not at) the cutting edge for ProFile and ProTaper Universal instruments. The overall magnitude of von Mises stresses in ProFile was lower than for ProTaper or ProTaper Universal. When the node with initially the highest von Mises stress was followed for a completion revolution, the stress value that it experienced varied in the form of a sine function (not shown). The operating stress amplitude, ie, difference between the peak and the trough (lowest) value in each load cycle, was the greatest for the ProTaper model (not shown).

After the instrument was withdrawn from the canal and assuming complete recovery of the elastic strains, residual stress could be noticed along the length of all instruments, with the location of such maximum stress corresponding well with that of maximum curve of the canal (Fig. 3). The highest value of residual stress was observed for the ProTaper instrument, which was situated at the cutting edge; the value was close to the phase transformation stress of 504 MPa. In contrast, a lower mag-

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