0099-2399/88/1407-0346/$02.00/0
JOURNAL OF ENDODONTICS

Printed in U.S.A.
VOL. 14, NO. 7, JULY 1988

An Initial Investigation of the Bending and Torsional Properties of Nitinol Root Canal Files

Harmeet Walia, BDS, MDS, MS, MS, William A. Brantley, BS, MS, PhD, and Harold Gerstein, BS, DDS

Root canal files in size #15 and triangular cross-sections were fabricated from 0.020-inch diameter arch wires of Nitinol, a nickel-titanium orthodontic alloy with a very low modulus of elasticity. A unique manufacturing process was used in which the fluted structure of a K-type file was machined directly on the starting wire blanks. The Nitinol files were found to have two to three times more elastic flexibility in bending and torsion, as well as superior resistance to torsional fracture, compared with size #15 stainless steel files manufactured by the same process. The fracture surfaces for clockwise and counter-clockwise torsion were observed with the scanning electron microscope and exhibited a largely flat morphology for files of both alloy types and torsional testing modes. It was possible to permanently pre-curve the Nitinol files in the manner often used by clinicians with stainless steel files. These results suggest that the Nitinol files may be promising for the instrumentation of curved canals, and evaluations of mechanical properties and in vitro cutting efficiency are in progress for size #35 instruments.

It is well known by clinicians that inadvertent procedural errors can occasionally arise during the instrumentation of curved canals. These misfortunes include ledge or zip formation, perforation of the canal, and separation or fracture of the instrument (1). As a consequence, the root canal morphology is adversely altered, a violation of the basic principle that endodontic preparation is to retain the original shape of the canal. Clinicians have adopted various methods to circumvent problems with the preparation of curved canals, such as precurving instruments and using a telescopic filing technique (1–3). Weine (4) has suggested that clinicians might remove the tips of instruments at chairside to make intermediate sizes for use in the preparation of curved canals.

The procedural errors which may occur during the instrumentation of curved canals have a common genesis: the basic stiffness of the stainless steel alloys (5) utilized for the manufacture of root canal files and reamers. Moreover, there is a substantial rise in instrument stiffness with increasing instrument size (6). For example, with the stainless steel files and reamers, the smaller sizes of instruments have considerably greater flexibility and can conform much better to the morphology of curved canals.

While manufacturers have recently marketed a number of new instruments based upon different cross-sectional shapes, design concepts, and fabrication procedures, in a quest for improved cutting efficiency (7) and flexibility (8), all of these brands have been fabricated from stainless steel. In this article we report the first use of an entirely new metallurgical system, Nitinol nickel-titanium orthodontic wire alloy (9), for the fabrication of endodontic files. The Nitinol alloy has a very low modulus of elasticity, only one-fourth to one-fifth the value for stainless steel, and a very wide range for elastic deformation.

The purposes of this initial study were to investigate the feasibility of manufacturing root canal files from Nitinol and to evaluate the bending and torsional properties of these instruments. The results of our laboratory study suggest the possibility of a new generation of files, possessing a degree of flexibility which may be ideally suited for instrumenting curved canals.

MATERIALS AND METHODS

Standard preformed Nitinol arch wire blanks, 0.020 inch in diameter, were obtained (Unitek Corp., Monrovia, CA), and two 2-inch straight segments from each arch wire were used for instrument fabrication. A unique file manufacturing process was used (Quality Dental Products, Johnson City, TN), in which the fluted cross-sectional shape was machined directly on the wire blank, rather than the conventional (10) manufacturing procedure of twisting the ground and tapered blank. For this initial feasibility study, experimental Nitinol root canal files were fabricated in size #15 and triangular cross-sections, for comparison to size #15 stainless steel files with the same cross-sectional shape and manufactured by the same process, which served as the controls.

The Nitinol and stainless steel files were evaluated in the three mechanical testing modes of cantilever bending, clockwise torsion, and counterclockwise torsion, following the experimental methods previously used by Krupp et al. (8). Values of bending and torsional moment were measured with a sensitive torque meter (model 783-C-1; Power Instruments, Inc., Skokie, IL), using a manual-loading experimental procedure and an apparatus based upon the original form of American Dental Association specification no. 28 (11). All specimens were subjected to bending or twisting at a point 3 mm from the apex of the instrument. For the bending tests, the specimens were loaded at 10-degree increments to a total angular deflection of 90 degrees. The specimens for the clockwise and counterclockwise torsion tests were loaded at 45-degree increments to an angular deflection of 360 degrees and thereafter at 90-degree increments until instrument fracture. There were five specimens or replications in each test group, and values of moment at each bend angle or twist angle were averaged and plotted to obtain graphical representations of mechanical behavior. From these graphs it was possible to compare the important practical mechanical properties of the Nitinol and stainless steel files: the relative flexibility and the resistance to fracture in torsion. In addition, scanning electron microscopic (SEM) photographs were obtained for files in the as-received condition to observe the effects of the manufacturing process and after torsional failure to compare the fracture surface morphologies for the two groups of files.

RESULTS

Scanning electron microscopic photographs of the tip and body regions are shown in Figs. 1 and 2 for the as-received Nitinol files and in Figs. 3 and 4 for the as-received stainless steel files. The rounded or Roane (12) tip design, the machining marks along the faces of the flutes, and the ridges of permanently deformed metal (rollover) along the cutting edges are characteristic features of the proprietary manufacturing process for these instruments. The extent of metal rollover was much less for the stainless steel files, which were subjected by the manufacturer to an electropolishing procedure, than for the Nitinol files which were not electropolished.

The Nitinol files had considerably greater elastic flexibility than the stainless steel files in all three testing modes of bending, clockwise torsion, and counterclockwise torsion (Figs. 5 to 7). This follows from a comparison of the slopes of the initial, approximately linear, portions of these plots; the slope is two to three times greater for the stainless steel files. The initial slopes of the two plots in Figs. 5 to 7 cannot be compared with precision because there is some arbitrary judgment in how these curves should be drawn for the lowest moment values. The pointer on the torque meter obscures

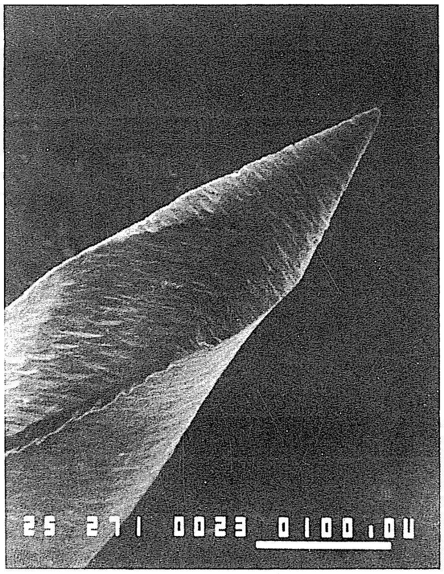

Fig 1. Scanning electron microscopic photograph of the tip region of a size #15 Nitinol file. The information on all of the legends for the SEM photographs is as follows, from *left* to *right*: accelerating voltage in kV; magnification; exposure number; scale marker for indicated distance in micrometers (original magnification ×271).

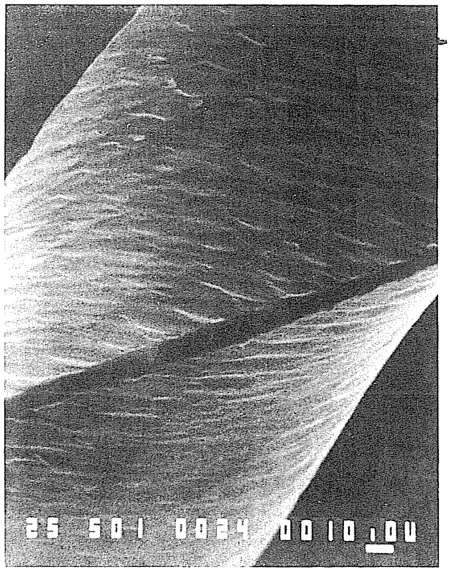

Fig 2. SEM photograph of the body region of a size #15 Nitinol file. The machining marks and the ridge of permanently deformed metal along the cutting edge are evident at this higher magnification.

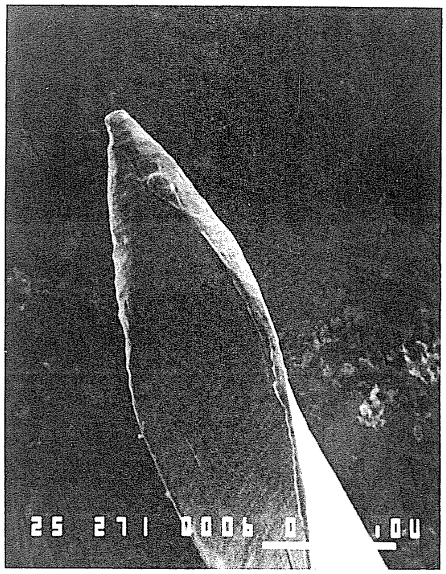

Fig 3. SEM photograph of the tip region of a size #15 Quality Dental Products stainless steel file. A rounded tip design is used for both the stainless steel and Nitinol instruments.

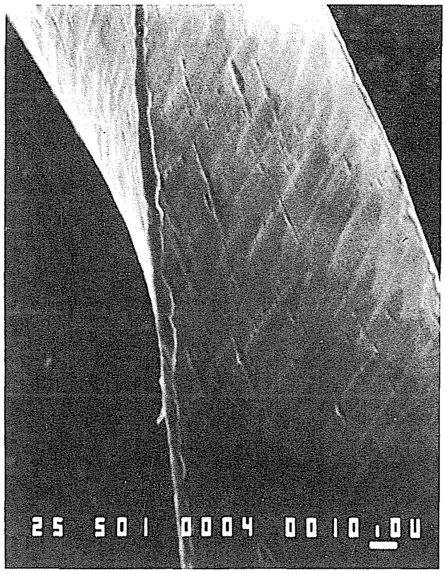

FIG 4. SEM photograph of the body region of a size #15 Quality Dental Products stainless steel file. An electropolishing procedure, not utilized for the Nitinol files, was used to reduce the machining damage on the stainless steel file surfaces.

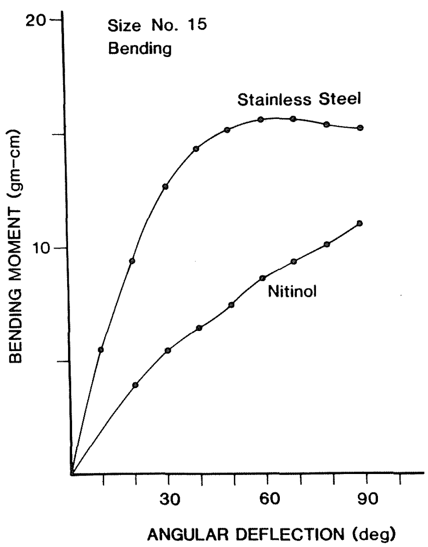

FIG 5. Cantilever bending test results for the size #15 Nitinol and stainless steel files. The data points in this figure and in Figs. 6 and 7 correspond to average moment values for groups of five instruments at the indicated bend or twist angles.

the reading of bending or torsional moments less than 0.05 inch-oz (3.60 gm-cm). Consequently, the passive position (zero moment value) and the corresponding location for zero angular deflection cannot be determined directly in an experiment. For convenience, all of the graphical plots have been drawn to intersect the origin. This extrapolation appears to be more satisfactory for the bending plots (Fig. 5) and clockwise torsion plots (Fig. 6) than for the counterclockwise torsion plots (Fig. 7).

The forms of the bending curves in Fig. 5 indicate that permanent deformation of the 3-mm apical regions of the stainless steel files began at a bend angle of approximately 30 degrees, but that the apical regions of the Nitinol files were undergoing largely elastic deformation even at bend angles of 90 degrees. The latter was supported by visual observations of the Nitinol files after unloading, where very little, if any, permanent bends were evident.

The Nitinol files also exhibited considerably greater resistance to fracture in torsion than the stainless steel files. For

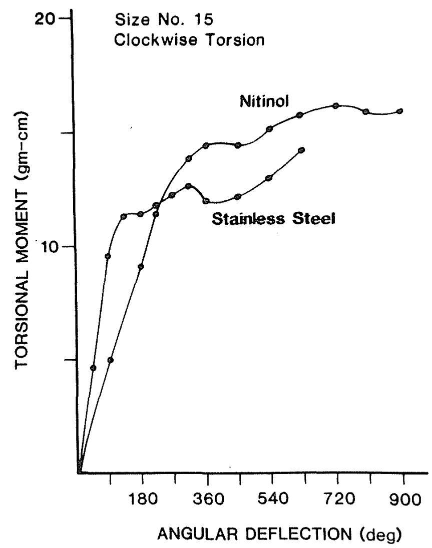

FIG 6. Clockwise torsion test results for the size #15 Nitinol and stainless steel files.

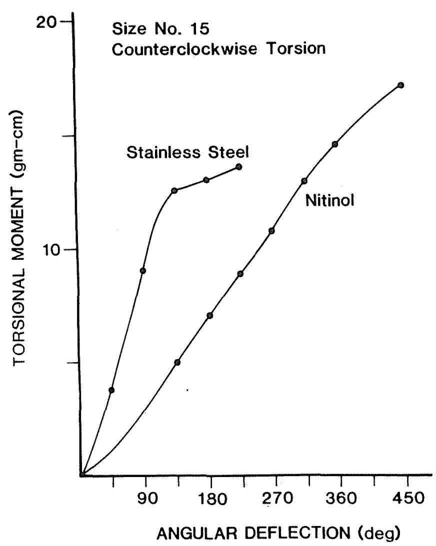

FIG 7. Counterclockwise torsion test results for the size #15 Nitinol and stainless steel files. The two initial data points for the Nitinol files could not be determined with the torque meter, and the two plots have been drawn to intersect the origin. Both of these considerations are less pronounced in Figs. 5 and 6.

clockwise torsion (Fig. 6), the size #15 Nitinol files were capable of undergoing a mean value of 2½ revolutions before fracturing, while the stainless steel files fractured after a mean value of 1¾ revolutions. The general appearances of the two clockwise torsion plots in Fig. 6 are very similar. The relatively extensive, nearly horizontal, portions of these two graphs indicate that the apical regions for both groups of files underwent substantial permanent torsional deformation before fracturing. An interesting point is that for clockwise twist angles exceeding 270 degrees the Nitinol files developed approximately 10 to 20% higher torsional moment than did the stainless steel files.

For counterclockwise torsion (Fig. 7), the Nitinol files experienced largely elastic deformation before fracturing at a mean value of 450 degrees angular deflection (1¼ revolutions). The stainless steel files fractured at a mean value of 225 degrees (between ½ and ¾ revolution), and the counterclockwise torsion plot for these instruments displayed a definite, although not an extensive, horizontal region corresponding to permanent deformation from 135 to 225 degrees. When the differing scales of Figs. 6 and 7 and the uncertainty of extrapolation to zero moment values are considered, it can be seen that the counterclockwise torsion plots are quite similar to the corresponding clockwise torsion plots over the same range of angular deflection.

The SEM photographs of the fracture surfaces for the Nitinol and stainless steel files after torsional failure showed essentially the same general characteristics (Figs. 8 to 11). The clockwise torsional fracture surfaces for the Nitinol (Fig. 8) and stainless steel (Fig. 9) instruments were largely flat and inclined to the axes of the files; nonplanar regions of fracture were observed near corners of the triangular cross-sections. The counterclockwise torsional fracture surfaces for both the Nitinol (Fig. 10) and stainless steel (Fig. 11) files were quite flat and differed little in appearance.

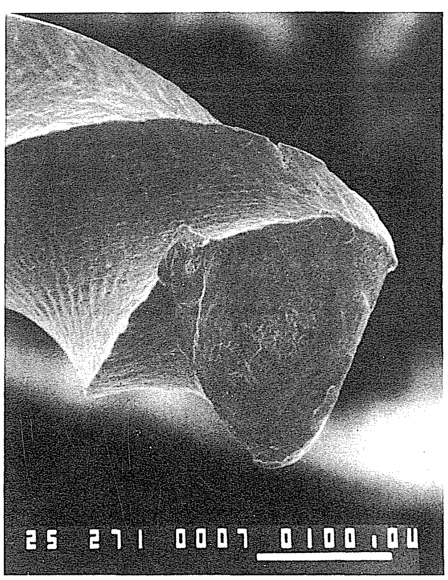

FIG 8. SEM photograph of the 3-mm apical region of a size #15 Nitinol file which has been tested to fracture in clockwise torsion.

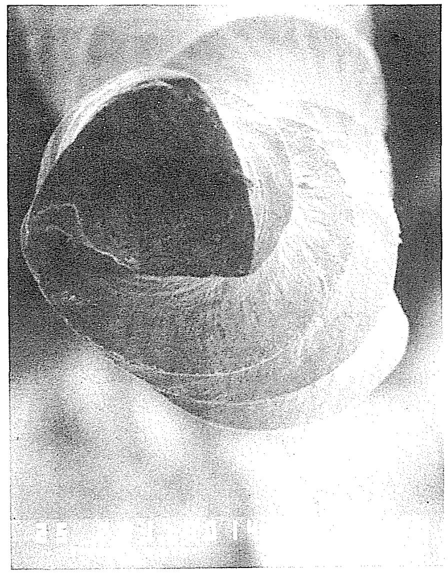

FIG 9. SEM photograph of the 3-mm apical region of a size #15 stainless steel file which has been tested to fracture in clockwise torsion.

FIG 10. SEM photograph of the 3-mm apical region of a size #15 Nitinol file which has been tested to fracture in counterclockwise torsion.

DISCUSSION

This initial study has demonstrated that root canal files fabricated from Nitinol orthodontic wires possess very promising bending and torsional properties. Our experimental results indicate that for size #15 the new metallurgical files have superior mechanical properties to the stainless steel files which were manufactured by the same process of directly machining the flutes for K-type instruments.

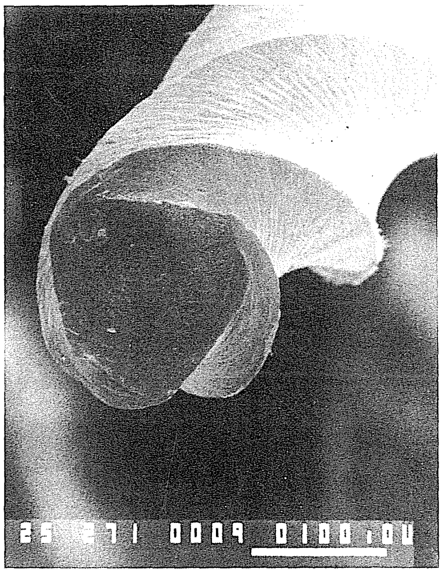

FIG 11. SEM photograph of the 3-mm apical region of a size #15 stainless steel file which has been tested to fracture in counterclockwise torsion.

The outstanding elastic flexibility of the Nitinol files is a consequence of the very low elastic modulus of these nickel-titanium alloys. Although there are complexities introduced by the fluted and tapered cross-sections, the slopes of the initial elastic, approximately linear, regions of the bending and torsion plots should be proportional to the modulus of elasticity in tension (Young's modulus) and the modulus of elasticity in torsion (shear modulus), respectively, of the Nitinol and stainless steel alloys (13). Experimental measurements have shown that the modulus of elasticity in tension for Nitinol orthodontic wires is only about one-fourth to one-fifth that for stainless steel orthodontic wires (14). Although experimental values of shear modulus are not available for these two orthodontic alloys, it can be readily shown that the shear modulus has approximately 40% of the value of Young's modulus for a given metal (15). Consequently, the shear modulus for the Nitinol orthodontic alloy should also have a value of about one-fourth to one-fifth that for the stainless steel wire alloy used to fabricate the root canal files. As previously noted, the slopes of the initial linear portions of the bending and torsion plots for the Nitinol files in Figs. 5 to 7 are approximately one-half to one-third the values of the corresponding slopes for the stainless steel files. The discrepancy between the observed and theoretically predicted relative slopes is attributed to the difficulty in drawing the exact forms of the bending and torsion plots at small values of angular deflection, particularly for the Nitinol files, and perhaps to small differences in cross-sectional dimensions of the nominally same size #15 instruments. The dependence of instrument stiffness on size has been discussed by Craig et al. (6).

The resistance to torsional fracture for the experimental Nitinol root canal files was clearly superior to the behavior of the control stainless steel files manufactured by the same process in size #15 (Figs. 6 and 7). Comparison of the present data to the results of a previous extensive study (8) in our laboratory on several brands of K-type files indicates that the process of machining the fluted structure does not appear to have substantial adverse effects on the tendency of the files in size #15 to fracture during torsion testing.

Standard K-type root canal files were not used as controls in our study because extensive data for bending and torsional properties from seven different brands in size #15 were available from the recent investigation by Krupp et al. (8) and because we needed control files fabricated by the same process used for the experimental Nitinol files. It was found that the stainless steel control files manufactured by Quality Dental Products yielded graphical plots of bending moment and torsional moment versus angular deflection that were similar to plots for the Kerr K-Flex and Whaledent brands in the same size which had been previously (8) evaluated. Because careful attention in the present study was directed to locating the D_3 position in the test grips and to maintaining the proper instrument test spans for the bending and torsion experiments, five replications in each group of Nitinol and stainless steel files were found to be sufficient. The five individual values of bending or torsional moment at each value of angular deflection generally did not differ much, with coefficients of variation (ratio of standard deviation to mean value) typically about 10%. Krupp et al. (8) had previously found that a sample size of five for each group of instruments was adequate for similar carefully performed bending and torsion tests with our manually loaded torque meter apparatus.

The superior torsional ductility, or resistance to fracture, of the Nitinol root canal files, compared with the stainless steel instruments evaluated in this study, was an unanticipated result. It is well known that orthodontists experience considerable difficulty with the placing of permanent bends in the very flexible Nitinol alloy (9), and we have felt that the conventional process (10) of twisting the ground and tapered wire blank might not be feasible for the fabrication of K-type root canal files from Nitinol. However, the inherent torsional ductility of this nickel-titanium alloy is evident from the clockwise torsion plot of Fig. 6, and the SEM photographs (Figs. 1 and 2) of the metal rollover ridges along the cutting edges of the flutes further attest to the capability of Nitinol for permanent deformation. Substantial permanent tensile deformation of Nitinol arch wires was also observed in a previous study (14) in our laboratory on the bending and tensile properties of orthodontic wires. The likelihood of ductility for Nitinol had been implied from the tabulated mechanical property information in the earlier review article by Civjan et al. (16), who discussed some potential dental applications for these nickel-titanium alloys. The authors suggested that 60-Nitinol, which is much harder than the 55-Nitinol orthodontic wire alloy (9), would have excellent characteristics for endodontic instruments, but they did not provide any further discussion of this application.

With Nitinol root canal files, the endodontist may choose to alter some of the clinical procedures presently used with stainless steel files in the preparation of curved canals. Because of the pronounced "elastic memory" characteristics of this alloy, the clinician may not consider it necessary to precurve Nitinol files to conform to the morphology of curved root canals. Nonetheless, we have found that the size #15 Nitinol files can be precurved, so this capability is available for these experimental instruments.

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