# Compressibility and the advantages of compression cutting of ProTaper NEXT™

Dr. Michael J. Scianamblo and Mr. Martin Flatland explore some advantageous properties of this file system

## Abstract

### Introduction

This study investigates the unique properties ProTaper NEXT™, a file that displays an offset cross-sectional center of mass and its concomitant compressibility.

### Methods

Specific tests using custom-designed fixtures were developed to measure the X-File compressibility in comparison to a traditional design ProTaper Universal or F-Files. The files were compressed by applying a force to the test file perpendicular to the axis of rotation. The compression or movement of the file due to the applied load was measured, and the X-Files were compared with the standard F-File.

### Results

The X-Files exhibited a range of elastic compressibility as a result of an applied load. This compressible range was seen when the applied load was between 1 N and 10 N. The amount of compression of the X-File (deflection) in this low-force range was between .05 mm and .15 mm, depending upon the diameter of the file cross section that was tested. The traditional endodontic file required a larger applied force, typically greater than 25 N, to show any significant deformation.

### Conclusions

The X-Files exhibit substantial elastic compressibility of between 0.05 mm to 0.15 mm compared to traditional F-Files, where the compressibility was found to be negligible. The amount of compression is dependent upon file curvature and the cross-sectional area of file under observation. This compressibility feature can lend itself to cut and remove material more efficiently and more safely.

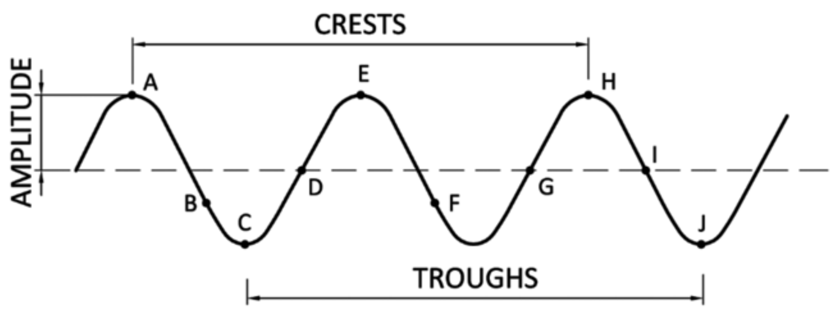


Figure 1: Depicts a transverse wave, which consists of oscillations occurring perpendicular or at right angles to the direction of the wave. The waves are composed of crests and troughs with a specific amplitude that determines the energy or force transmitted by each wave

## Introduction

Traditional endodontic instrument designs have a center of rotation and a center of mass that are identical, dictating a linear trajectory or path of motion. These designs, of course, facilitate elastic memory and the restoration of the original file shape. The use of nickel-titanium in the manufacture of endodontic files further facilitates this function. This has been thought to be of paramount importance during root canal preparation, whereby the restoring force can be pitted against the balancing force as described by Roane, et al. (1985) and Southard, et al., (1986). However, the work of Peters (2001) has indicated that it is this precise function that prevents the instruments from contacting the root canal walls, leaving as much as 35% of the internal anatomy of the canal untouched and the preparation poorly centered.

In addition, the work of Sattapan, et al. (2000), Spanaki-Voredi, et al. (2006), Kramkowski and Bachall (2009), and others indicates that instrument binding and cyclic fatigue with subsequent instrument failure remains a common problem with nickel-titanium instruments.

An alternative approach to traditional instruments designed with a coincident center of rotation and center of mass are instruments that have an "offset" cross-sectional center of mass from the center or axis of rotation. These instruments have been described as swaggering files but are more accurately defined as instruments that cut on a precessional axis or via a cyclical wave and are currently marketed under the trade name ProTaper NEXT. Precession describes the motion that occurs whenever the axis about a body, which is spinning, is itself rotating about another axis.

When the center of mass of the cross-sectional area of a file is offset, the cutting motion is no longer linear in mechanical terms, but helical or cyclical. Swagger, or in more sophisticated terms, precession, is viewed as a mechanical wave that travels along the length of the file. As with any wave traveling through a medium, a crest is seen moving

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Martin L. Flatland, BSME, has more than 20 years of experience in biomedical engineering and new product development and is the CTO and Chief Engineer of SiteSelect Medical Technologies. Dr. Flatland has also worked in R&D for both Richard Allan Medical and Imagyn Medical Technologies and began his engineering career at Stryker Medical, where he worked on the product team that developed the first electrically controlled patient handling unit. Dr. Flatland holds 16 U.S. patents and is listed as the primary inventor on four pending U.S. patent applications. He holds a BSME and has completed graduate work in mechanical engineering at Western Michigan University. He has maintained memberships in Tau Beta Pi Engineering Honor Society and the American Society of Mechanical Engineers.

from point to point. This crest is followed by a trough, which in turn, is followed by the next crest. The wave pattern that is generated by ProTaper NEXT is a transverse wave pattern.

Transverse waves oscillate perpendicular to the direction of propagation. For example, if you anchor one end of a rope and hold the other end in your hand, you can create transverse waves by moving your hand up and down (on the z-axis). Notice, however, that you can also create waves by moving your hand side-to-side (on the y-axis).

ProTaper NEXT is configured to oscillate or spiral in both the y-axis and the z-axis, while the wave propagates along the x-axis. This cyclical wave pattern or precessional cutting axis is inscribed in the design of ProTaper NEXT by offsetting a rectilinear cross section (Figure 2), which revolves around the central axis as shown in the SEM in Figure 3 (courtesy of Dr. Sergio Kutler) and the "wire perspective" in Figure 4 below.

The performance of such a design is difficult to describe in two-dimensions. Thus, the reader is referred to a video provided by the following link: https://www.youtube.com/watch?v=dNHzySw51Uk.

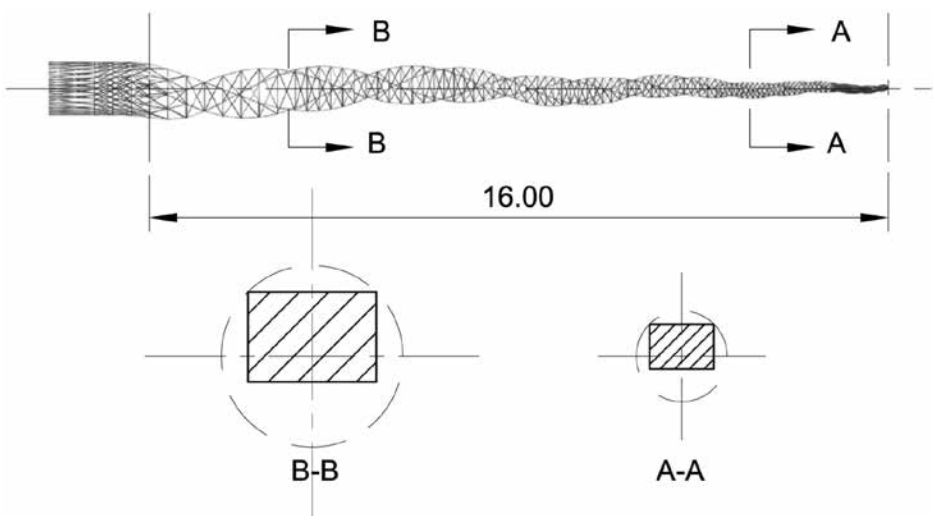
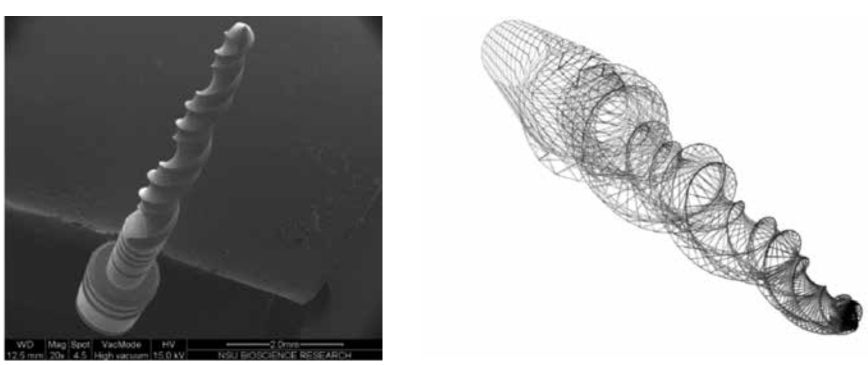



Figure 2: A schematic of offset rectilinear cross section of ProTaper NEXT. As can be seen from this figure, only two cutting angles engage the walls of the root canal at any one time. This offset rectilinear cross section not only contributes to the innate flexibility of the file, but also permits intermittent cutting, which mitigates cyclic fatigue. The large clearance angle opposite the cutting flutes facilitates hauling and elimination of debris



Figures 3-4: An SEM of the profile and an Auto-CAD image of the X-File demonstrating the spring or coil-like profile of the instrument

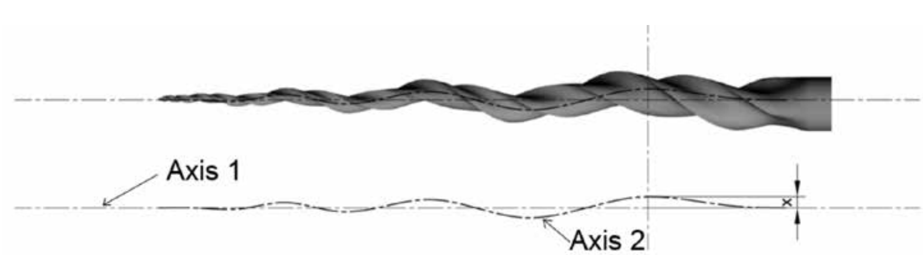



Figure 5: A schematic of the profile and dual axis of Protaper NEXT. Axis 1 is the central or rotational axis, and Axis 2 is the cutting or precessional axis. The distance-X between the two axes decrease continuously from shank to tip, where the axes meet, leaving the tip completely centered. The offset center of mass, inherent in this design, enables the X-File to cut precessionally

The SEM and the wire perspective shown can lend to the visualization of "compressibility" of these files.

Previous to ProTaper NEXT, Hof, et al. (2010); Metzer, et al. (2010); and Peters and Paque (2011) described an ultrasonic instrument called the Self-Adjusting File, which displayed a compressible lattice with the capability of adapting itself to the canal shape, improving centering and reducing the amount of unprepared tooth structure. Ruckman, et al. (2013) demonstrated that the Self-Adjusting File was significantly better than hand instrumentation in cleaning long-oval-shaped canals at mid-root. Until now, there have been no reports of rotary instruments, which feature the property of compressibility. The following discussion describes such an instrument.

## Description

As previously mentioned, ProTaper NEXT represent a new concept in endodontic file design, in which the center of mass of the cross-sectional area is offset from the center of rotation. The axis of rotation or central axis of the X-File, which defines the theoretical center of rotation, is shown by Axis 1. Axis 2 follows the geometric center of the X-File. The amount of offset between the center of rotation and the center of mass is defined by the distance between these two axes and varies along the length of the file and shown as the distance-x (Figure 5).

During instrumentation of the root canal, typically at 300 rpm to 350 rpm and 2 Ncm to 4 Ncm, the geometric axis or Axis 2 shown in Figure 5, becomes a precessional axis. As mentioned previously, when the X-File is rotated, it produces a transverse mechanical wave defined by a series of peaks and troughs. The amplitude or heights of the peaks are at a maximum when the file is in its free and unconstrained position. When the file is inserted into the root canal, the peaks will be compressed. The amount of compression will depend upon the diameter and the curvature of the canal. Theoretically, when the file is fully compressed, Axis 2 will flatten out and be collinear with Axis 1. As each peak along the file is elastically compressed, it behaves like a small spring and is a source of potential or stored energy.

## Analysis of the file as a variable rate spring

Another factor that must be considered in understanding the function of the X-File is the file stiffness and/or flexibility. The X-File possesses the unique property of a coil or spring, which differentiates it from the traditional endodontic files. Stiffness and/or flexibility is often referred to as a spring constant, which is defined as the amount of force that is required to cause a unit of deformation. In its general form, $k = F / \delta$, where k equals the stiffness, F equals force, and $\delta$ equals displacement. Equations for the determination of the spring constant of actual mechanical systems are widely available in engineering literature. Due to the constantly changing cross section of the X-File, the spring constant of the file will vary along its length. This spring constant, together with the file precession, directly affects the cutting forces applied to the surrounding root dentin during application.

In one respect, we can look at a localized section of the file as it is bent to conform to the canal shape during use, shown as L in Figure 6. If we define the localized section of the file to be analyzed using the terminology defined in the waveform discussion earlier, we can analyze the spring rate of a single wave crest between two nodes. In this application, the stiffness can be analyzed using the equations for a simply supported beam in Figure 7.

L represents the distance between any two nodes; I represents the moment of inertia, which is dependent upon the cross-sectional area of the file and will vary along its length; and E represents the modulus of elasticity (Young's Modulus), which is used to define the stiffness of different materials.

We define the variables presented in Figures 6 and 7 with respect to the X-File as follows:

- L would represent the distance between any two nodes.
- I represents the moment of inertia, which is dependent upon the cross-sectional area of the file and will vary along its length.
- E represents the modulus of elasticity (Young's Modulus), which is used to define the stiffness of different materials.

When we evaluate the initial conditions of the X-File as it is inserted into a root canal, we look at the reverse of what is depicted in Figure 7 above and shown in Figure 8. The instrument shown in Figure 8 is in its constrained or compressed condition. Here F represents the force exerted on the file by the canal wall. Since the X-File is built with multiple nodes and potential deflections, the tendency of F will be to straighten out the file along its length. When the file is fully constrained, x, which represents the deflection of the file due to F, would initially be zero (or nearly zero). As the file begins to rotate, its tendency will be to return to the natural state in which it is precessing about its central axis. As it attempts to precess, the cutting edges, under the load of the spring force, will begin to remove material from the surrounding cavity. This process will continue until the file has enlarged the canal based the file diameter and the precession axis. In this final unconstrained condition, shown in Figure 9, the spring force or cutting force will be nearly zero, and the file will be rotating freely about the central axis.

A design of this nature would theoretically allow the instrument to engage the intaglio of the root canal space intermittently as the constrained coil is inserted in the canal and allowed to unwind, releasing a theoretical

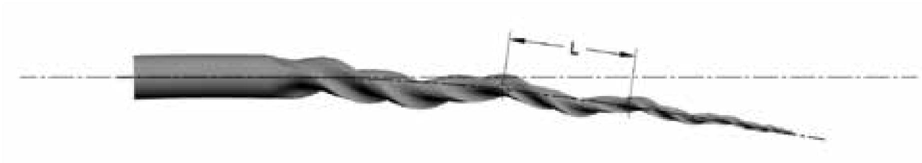



Figure 6: Demonstrates the localized section of the file as it is bent to conform to the cavity during use. L is the distance between the crest of two nodes, with which we can analyze the spring rate of a single wave between the crests

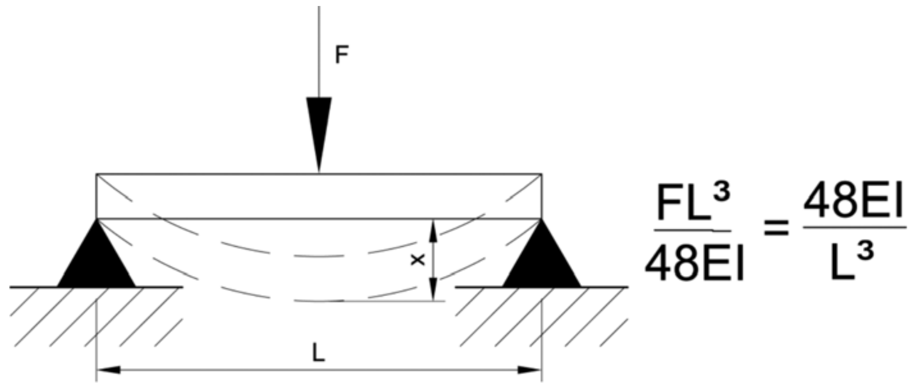
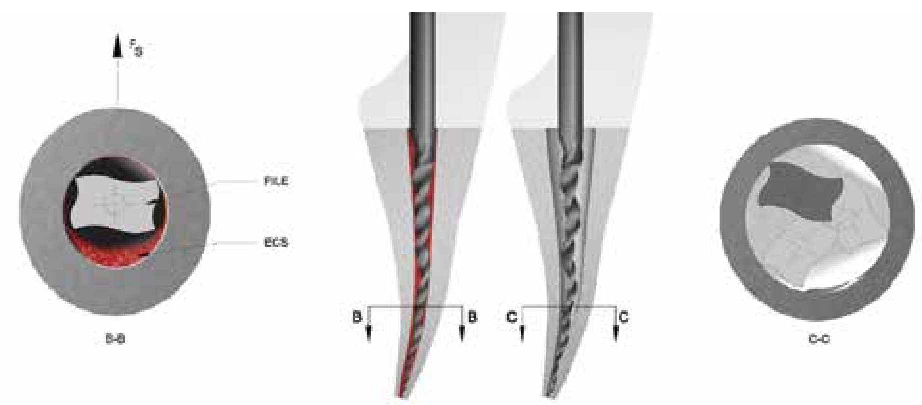
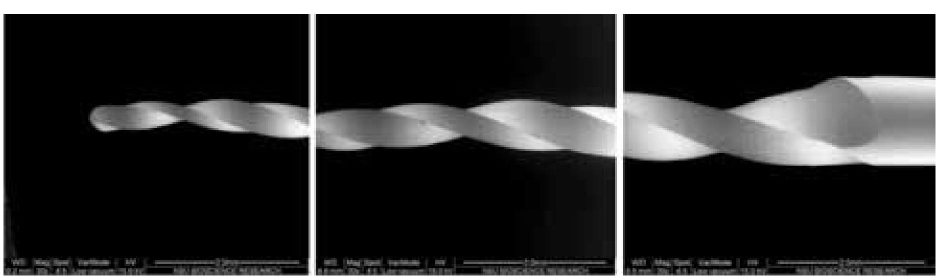


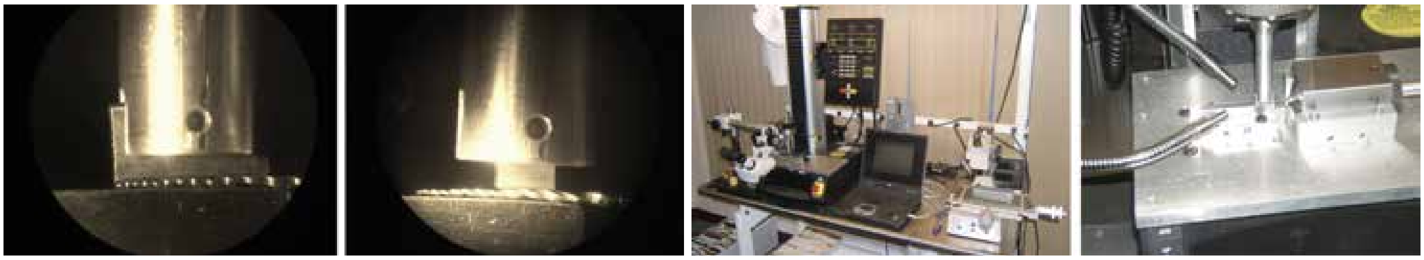

Figure 7: A schematic of a simply supported beam and the equation used to determine the stiffness or restoring force of the simply supported beam (where x is the maximum reflection)




Figures 8-9: Demonstrates the instrument in its constrained or compressed condition. When the file is fully constrained, x (as shown in Figure 5), which represents the deflection of the file due to F, would initially be zero or nearly zero. Demonstrates the file's tendency will be to return to the natural or uncompressed state in which it is precessing about its central axis



Figures 10A -10C: Scanning electron micrograph of the instrument itself demonstrating the nodes of the file and the instrument in the unconstrained or uncompressed condition



Figures 11A-11D: A. Illustrates a custom fixture used to measure the force applied perpendicular to the central axis (Figure 5, Axis 1) of the file. This testing was performed to measure the compressibility over the full length of the file. B. Illustrates the custom fixture used to measures the compression at individual peaks along the length of the file. The test setup is similar to that used for the full length testing. C-D. Equipment used for testing included an Instron Model 4442 Tension/Compression Tester, a DAQ (Data Acquisition System), custom fixturing to position the files for testing, a Toolmakers microscope, a stereo microscope, and miscellaneous measuring equipment, including a, micrometer, calipers, and gage pins

amount of stored energy. The release of stored energy is dissipated gradually, which minimizes binding, which would mitigate cyclic fatigue, while providing the opportunity to clean both inner and outer curvature of the canal wall more thoroughly.

This mitigation of cyclic fatigue has been verified by Pérez-Higueras, et al. (2014); Nguyen, et al. (2014); and Elgnaghy, et al (2014). These finding are particularly impressive considering that the cross-sectional area of X-Files is approximately 30% narrower in the y-axis and 40% narrower in the z-axis when compared to the F-Files (Scianamblo, 2016).

In addition to the mitigation of cyclic fatigue, Zhao, et al. (2014), who demonstrated that during the preparation of curved canals, PTN had less apical transportation than the canals prepared using WaveOne® or ProTaper® Universal, Arias, et al. (2014) found that instruments in ProTaper Next set showed greater regularity in peak torque for small and large canals than ProTaper Universal instruments, which implies an accommodation of the file under power.

Clinicians have also noted the ease with which ProTaper NEXT can negotiate complex anatomy, particularly severely curved canals and complex bends. These attributes have lent to the speculation that ProTaper NEXT is compressible, which lends to the following study.

## Objective

The objective of this study was to analyze the compressibility of the X-File compared to traditional designs and test the influence of the compressive forces on the ability of the X-File to cut material.

## Methods and materials

The tests used to investigate the compressibility of these instruments were specially designed. The endodontic files used included the ProTaper NEXT (X-File) and the ProTaper Universal (F-File). Both file types are constructed of nickel-titanium and

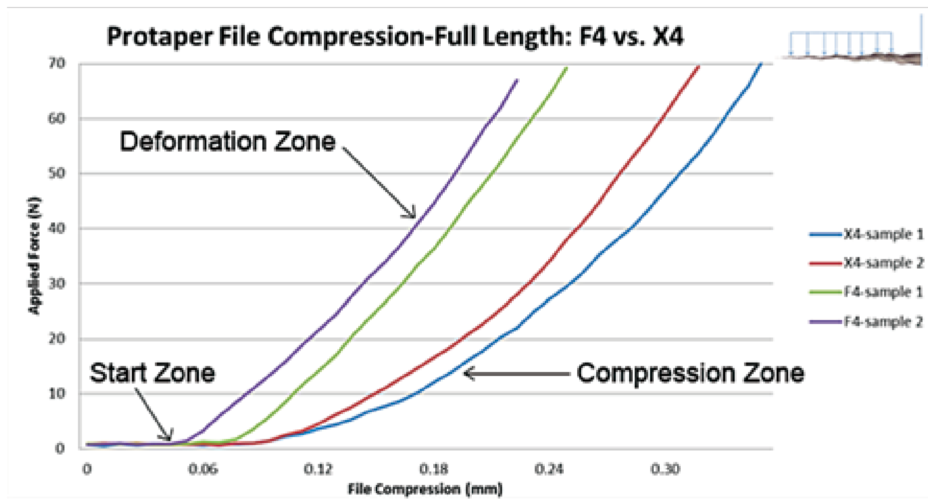



Figure 12: Shows a data plot comparison from the compression testing of the X4-File verses the F4-File. This plot is representative of the data plots of all of the files sizes tested. The response of the X-File to the applied load is clearly different from that of the F-File. For analysis purposes, the plot is divided into three zones as labeled in Figure 12

manufactured by Dentsply Maillefer (Switzerland) or Dentsply International. All files tested were 25 mm long. Equipment used for testing included an Instron Model 4442 Tension/Compression Tester, a DAQ (Data Acquisition System), custom fixturing to position the files for testing, a Toolmakers microscope, a stereo microscope, and miscellaneous measuring equipment, including a, micrometer, calipers, and gage pins.

## Compression testing: full file length

The compressibility testing performed here measures the amount of file compression when a force is applied perpendicular to the central axis (Figure 5, Axis 1) of the file. This testing was performed to measure the compressibility over the full length of the file. To perform the test, each file was inserted into a custom-testing fixture (Figure 11A). A microscope was used to locate the file in a pre-defined test position, and the file was then locked into this position. With the file locked in position, a compressive force was then applied along the length of the file using the full length applicator. The applied load and corresponding compression for each file tested was captured using a data acquisition system. Two sets of the X-Files and two sets of F-Files were tested. Each set included five files: for ProTaper NEXT sizes 17/04, 25/06, 30/07, 40/06, and 50/06 and for ProTaper Universal sizes 20/07, 25/08, 30/09, 40/06, and 50/05.

## Compression testing: localized

In an effort to more clearly define the file compression that is exhibited by the X- Files, this test measures the compression at individual peaks along the length of the file. The test set up is similar to that used for the full length testing. A localized force applicator is now used to apply the compressive force at specific points along the length of the file (Figure 6). ProTaper NEXT X-4 File (tip size 40) was used for this testing. ProTaper Universal or the standard file design does not exhibit any localized peaks or valleys, and therefore, this test is not applicable.

## Results

### Compression testing: full file length

There is a measurable difference in the compressive behavior of the X-File and the

F-File. This difference was consistent on all files tested. Figure 12 shows a data plot comparison from the compression testing of the X4 and F4 Files. This plot is representative of the data plots of all of the files sizes tested. The response of the X-File to the applied load is clearly different than that of the F-File. For analysis purposes, the plot is divided into three zones as labeled in Figure 12. Table 1 compares the file compression in the compression zone for all files tested.

Table 1: Comparison of the full length file compression in the compression zone

| File type and size | X1 | F1 | K2 | F2 | X3 | F3 | X4 | F4 | X5 | F5 |
|---|---|---|---|---|---|---|---|---|---|---|
| File compression (mm) at 10N | .114 | .0381 | .122 | .043 | .089 | .041 | .086 | .031 | .104 | .041 |

We see from the table that the X1 and the X2 files were the most compressible with a compressibility of 0.114 mm and 0.22 mm, the equivalent of two instruments sizes in the ISO system of file sizes

### Compression testing: localized

Localized compression testing was performed at four points along the length of the X-4 file, as represented in Figure 13. The distance of each point measured from the tip of the file is given in Table 2. The data from each test point was plotted and used to analyze the spring-like behavior for each wave of the file. During the compression testing of the files, we were able to measure both the force and the distance as the file was compressed along different points along its length. From these measurements, we were able to determine the Spring Rate (k). When the file is inserted into the cavity, it may be compressed. The amount of compression will depend upon the size of the cavity. When the file is a maximum compression, each wave exerts a force on the cavity wall. The size of the force based upon the spring rate is shown in the table. As the file rotates, this force is available to perform work (work = Force x distance). The amount of work available is shown in column 4 above. This work is available to cut and increase the cavity size without any (or nearly any) down force required. This is of particular importance, since the X-Files are one of the few files systems that do not require significant forcible apical pressure or a down force to engage them. This, of course, implies a lower operating torque and lends to the safety of the files.

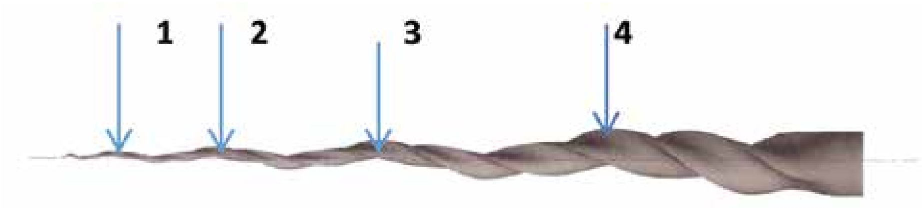



Figure 13: Localized compression testing was performed at four points along the length of the X-File as shown

Table 2: Measurements of the force and the distance as the file was compressed

| Test position | Distance from tip (mm) | Spring rate: k = δF / δx (N/mm) | Available work: W = ΔE = 1/2 k(δ22-δ12) |
|---|---|---|---|
| 1 | 2.5 | 60.9 | 0.073 |
| 2 | 5.7 | 62.3 | 0.167 |
| 3 | 10.8 | 76.1 | 0.980 |
| 4 | 12.5 | 139.2 | 3.220 |

From these measurements we were able to determine the Spring Rate (k). As the file rotates, this force is available to perform work (work = Force x distance). The amount of work available is shown in column 4 above. This work is available to cut and increase the cavity size without any (or nearly any) down force required

## Discussion

ProTaper NEXT or the X-Flies demonstrate an elastic compression that is not present in the files designed with a traditional cross-sectional area that is centered such as ProTaper Universal. This compressibility is a result of the unique waveform design of the X-Files or ProTaper NEXT. Compressibility was observed in all of the X-Files tested, with the amount of compression being dependent upon file cross section and wave height. The difference in the behavior of the two file types is clearly shown in Figure 12. This graph is best analyzed by defining three sections: 1. Start Zone, 2. Compression Zone, and 3. File Deformation Zone. The start zone is represented by the flat line that starts each data set. The start zone is apparent in all files tested. The start zone represents the initial bending of the file as the force applicator bends the file downward until contact is made with the fixed anvil underneath the file. The applied force associated with the start zone ranges from 0.5 N to 1.1 N, depending upon the file under test. The resulting deflection range associated with the start zone is from zero to 0.13 mm. The start zone represents the force required to initially deflect each file along its length.

The compression zone is only apparent in X-File test data and clearly differentiates the compressive behavior of the X-File from the standard F-File. The compression zone represents the compression of the waveforms that are unique to the X-File. Depending upon the file under test, the compression range is seen typically between 1N and 10N applied force. In all files tested, the data shows that the X-Files typically compress between 0.13 mm and 0.20 mm in this force range. In comparison, the standard F-file typically compressed between 0.05 mm and 0.08 mm in this force range, which is negligible.

## Clinical ramifications and benefits

Taken in the context of instrument design and file diameters, upon full compression and deformation, a change from 0.10 mm to 0.20 mm is a net change of approximately 0.10 mm, which is the equivalent of two instrument sizes in the ISO file size system. For example, if the net compressibility of the X1 is 0.114 mm as shown in Table 1, the X1 (which is 17/04 at the tip) has a diameter of 0.24 mm at D3 (equivalent to a 25K file, but is convertible to a 0.14 when full compressed (equivalent to a 15k file).

The accommodation or translation of the file from a larger diameter to a smaller diameter would necessarily affect a number of clinical outcomes. As mentioned previously, ProTaper NEXT has been shown to have greater resistance cyclic fatigue. The characteristic of compressibility, however, should also allow the file to remain well centered, and transitioning from one file to the next should be easier — i.e., more regularity in peak torque. As mentioned, research done by Zhao, et al., demonstrated that during the preparation of curved canals, PTN had less apical transportation than the canals prepared using WaveOne or ProTaper Universal. And Arias, et al., found that instruments in ProTaper Next set showed greater regularity in peak torque

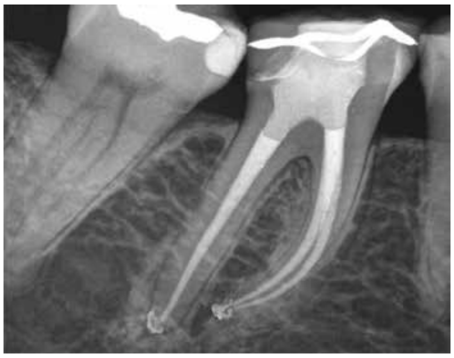


Figure 14: Postoperative radiograph of a lower first molar with three separate canals. The mesial canals were prepared with files X1 and X2 to the apex using X3 and X4 in the upper two-thirds of the canals in a back-stepping modality. The distal canal was prepared with X1, X2, and X3 to the apex using the X4 and X5 in the upper two-thirds of the canals in a back-stepping modality. The canals were obturated using Schilder technique (Courtesy of Dr. Darron Rishwain, San Rafael, California)

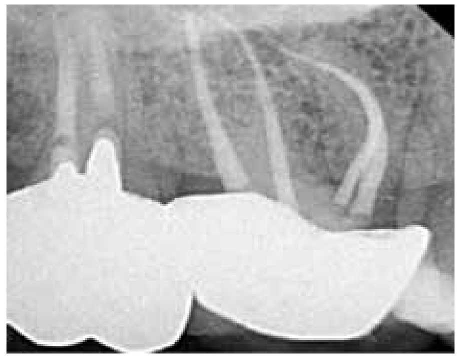


Figure 15: A postoperative radiograph of an upper first molar with severely dilacerated mesiobuccal canals. The mesiobuccal canals were prepared with files X1 and X2 only. The palatal and distobuccal canals were prepared with X1, X2, and X3. The canals were obturated using Schilder technique (Courtesy of Xenia Brant, Belo Horizonte, Brazil)

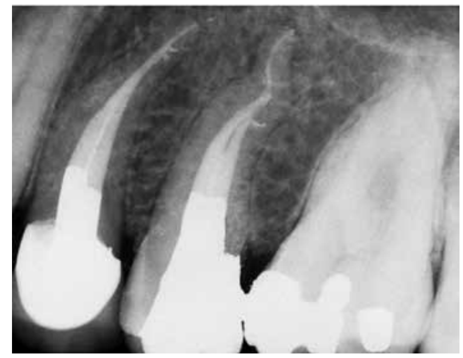


Figure 16: Postoperative radiograph of an upper second bicuspid with two canals. The canals were prepared with files X1 and X2 prototypes in the apical half. The coronal half was enlarged with the X3 and X4 in a step-back modality. The canals were obturated using Schilder technique or warm gutta percha (Dr. Michael Scianamblo, San Rafael, California)

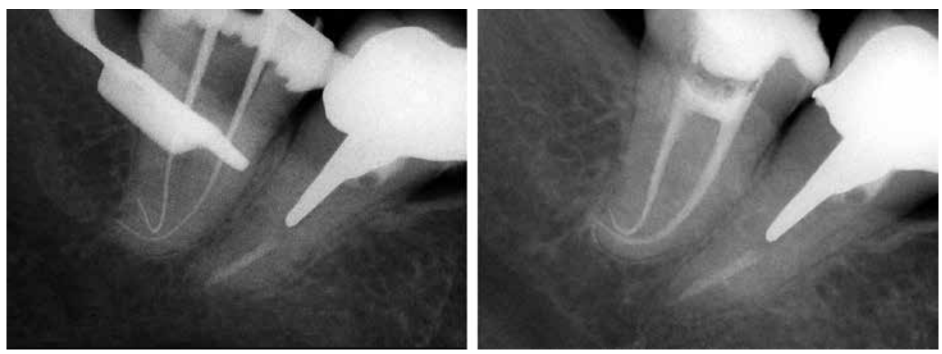


Figure 17: A postoperative radiograph of a lower third molar with severely dilacerated canals. The mesial and distal canals were prepared with files X1 and X2 only. The canals were obturated with Thermofil® (Courtesy of Dr. Giuseppe Cantatore, Milano, Italy)

for small and large canals than ProTaper Universal instruments, which implies that the instruments transition easily from one instrument to the next.

These benefits are manifest clinically, by the ability of the operator to negotiate severely curved, tortuous, and long canals without over enlarging the upper part of the canals as shown in Figures 14-17 above.

A clinical observation that has been reported by many clinicians using ProTaper NEXT is that the instruments must be used several times before the next largest file is introduced, for example, advancing from the X1 to the X2. This observation is due, again, to the compressibility of the file and the fact that that instruments are still constrained after the first introduction. Once the instrument is no longer constrained, advancement to the next largest file is forthcoming.

Tests are currently being developed to investigate other potential benefits; for example, cleanliness and interruption of the smear layer.

## Conclusion

The X-Files exhibit elastic compression due to an applied side load that differentiates them from traditional file designs. Compression of the X-File results in a store of potential (spring) energy, which allows the instrument to continue to expand as it rotates under power and to cut with little or no down force. When the file is rotated, the spring energy is converted to work done per unit time, which is effectively used to cut and remove material more efficiently, while lending safety to the system. EP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