The ultimate aim of endodontic therapy is the prevention of periradicular disease and the promotion of healing. To achieve these objectives, mechanical instrumentation and chemical disinfection are considered the basic principles, and the former essentially determines the efficacy of all subsequent procedures.

For gutta-percha fillings, the shaping of the canal should satisfy the following criteria:
- the shape of the main root canal should resemble a continuously tapering funnel from orifice to apex;
- the cross-sectional diameter of the main canals should narrow apically;
- preparation should follow the original shape;
- the position of the apical foramen should be preserved;
- the dimensions of the apical opening should be retained as far as possible.

The biological objectives of root canal instrumentation are:
- confinement of instrumentation to the limits of the roots themselves;
- avoidance of extruding necrotic debris into the periradicular tissue;
- removal of all organic tissue from the main and lateral canals; and
- creation of sufficient space to allow irrigation and medication by simultaneously preserving enough circumferential dentine for the tooth to function.

Achieving the aforementioned objectives in straight canals is considered a straightforward procedure. However, the internal anatomy of human teeth often consists of a highly complicated network of multiplanar curved and anastomotic canals. Reaching the biological and design objectives of root canal instrumentation in severely curved canal systems thus might be extremely challenging. Problems arise when canals are severely curved or even bifurcated and anastomotic (Fig. 1). In such teeth, the basic endodontic techniques and instrumentation protocols might be challenging to follow. For a safer and more predictable instrumentation, a newly introduced NiTi file sequence can be applied in the TCA technique.

Curved canal management

Based on canal curvature, Nagy et al. classified root canals into four categories:
1. straight or I-shaped (28 % of root canals);
2. apically curved or J-shaped (23 %);
3. entirely curved or C-shaped (33 %); and
4. multi-curved or S-shaped canals (16 %).

Schäfer et al. found that 84 % of root canals studied were curved, while 17.5 % of them presented a second curvature and were classified as S-shaped. Of all the curved canals studied, 75 % had a curvature of less than 27°; 10 % a curvature with an angle between 27 and 35°, and 15 % a severe curvature of more than 35°. Traditionally, root canal curvatures were described using the Schneider angle: root canals presenting an angle of 5° or less were classified as straight canals, root canals...
with an angle of between 10 and 20° as moderately curved and canals with a curve of greater than 25° as severely curved. Decades later, Pruett et al. reported that two curved root canals might have the same Weine angle, but totally different abruptness of curvature. In order to define the abruptness, they introduced the radius of a curvature: the radius of a circle passing through the curved part. In rotary instruments, the number of cycles before failure significantly decreases as the radius of curvature decreases and the angle of curvature increases.

Further attempts to mathematically describe curvatures in 2D radiographs introduced parameters such as the length of the curved part and the location as defined by curvature height and distance. Recently, Estrela et al. described a method for determining the radius of root canal curvatures using CBCT images analysed by specific software. Three categories were classified: small ($r \leq 4\, \text{mm}$), intermediate ($r > 4\, \text{mm}$ and $r \leq 8\, \text{mm}$) and large ($r > 8\, \text{mm}$). The smaller the radius of a curvature is, the more abrupt the curvature becomes. All these attempts to describe the root canal curvature had one goal: to preoperatively assess the risk of transportation and unexpected instrument separation.

**Canal transportation and instrument separation**

According to the *Glossary of Endodontic Terms*, “transportation” is defined as the removal of the canal wall structure on the outside curve in the apical half owing to the tendency of files to restore themselves to their original linear shape. For stainless-steel hand files and conventional hand- or engine-driven NiTi files, the restoring force of a given instrument is directly related to its size and taper. The larger the size or taper, the larger the restoring force, owing to the increase of the metal mass of the instrument. If instruments were constructed precisely on the dimensions of root canals, transportation would not be a problem: instruments would be well constrained inside the root canal trajectories. Unfortunately, instruments are not precisely shaped to fit canal dimensions. As a result, each instrument may follow its own trajectory inside a curved canal guided by its restoring force, thus transporting the canal.

Usually, dentinal removal towards the outer apical curve becomes more excessive if a greater increase in apical enlargement is attempted to be created. Consequently, the inner curvature widening can become excessive too. To avoid these complications, dentists sometimes tend to increase flaring and reduce apical instrumentation size in severe curves. Increasing flaring under such circumstances often results in the reduction of the angle of curvature, shortening the length, increasing the radius and relocating the curvature apically (Fig. 2). Smaller apical preparations in highly curved canals would be preferable for two reasons: (a) smaller-diameter preparations are related to less cutting of the canal walls, less file engagement and, consequently, a lesser likelihood of undesirable cutting effects; and (b) small-diameter files are more flexible and fatigue-resistant and therefore less likely to cause transportation during enlargement.

The aforementioned instrumentation approaches, although safer, have inherent disadvantages. Unfortunately, flaring the canal entrance in order to achieve easier negotiation to the apical third of curved canals will result in unnecessary removal of dentinal structure that is irreplaceable. Moreover, smaller apical preparations may result in increased difficulties in delivering irrigating solutions to an appropriate depth. In highly curved canals, the ability of irrigating solutions to reach the critical apical third depends directly on the ability to create adequate apical preparations and the selection of appropriate delivery techniques. Adequate apical preparation for disinfection without over-flaring the coronal part of highly curved canals is one of the great challenges in endodontics—especially according to the current concepts of dentinal preservation and minimally invasive dentistry.

Moreover, the risk of unexpected instrument separation of engine-driven NiTi files poses significant problems to canal management. Two mechanisms have been identified: cyclic fatigue and torsional failure. When an engine-driven instrument is activated inside a curved canal, continuous tensile and compressive stress at the fulcrum of the curvature may lead to instrument separation because of cyclic fatigue. If the tip of an engine-driven instrument is locked inside a canal and the shaft keeps on moving, it may exceed an applied shear moment, resulting in torsional failure. As the complexity of the curvature increases, the number of cycles before failure decreases.

![Fig. 2: The effect of flaring in the curvature parameters.](image-url)
Using controlled memory files

NiTi alloys are overall softer than stainless steel, have a low elasticity (about one-fourth to one-fifth that of stainless steel) but greater strength, are tougher and more resilient, and show shape memory and super-elasticity.\textsuperscript{16} The NiTi alloys used in root canal therapy contain approximately 56\% nickel and 44\% titanium.\textsuperscript{17} They can exist in two different temperature-dependent crystal structures called martensite (low-temperature phase) and austenite (high-temperature phase). The lattice organisation can be transformed from austenite to martensitic by adjusting temperature and stress. During the reverse transformation, the alloy goes through an unstable intermediate crystallographic phase called R-phase.

Root canal therapy causes stress to NiTi files: a stress-induced martensitic transformation of conventional NiTi files takes place instantly. A change in shape occurs with volume and density changes. This ability to resist stress without permanent deformation is called super-elasticity. The super-elasticity is most pronounced at the beginning, when a first deformation of as much as 8\% strain can be totally overcome. After 100 deformations, the tolerance is about 6\%, and after 100,000 deformations, it is about 4\%. Within this range, the memory effect can be observed.\textsuperscript{18}

Besides stress-induced martensitic transformation, the lattice organisation of NiTi alloys can be altered by altering the temperature. When a conventional NiTi austenitic microstructure is cooled, it begins to change into martensite. The temperature at which this phenomenon begins is called the austenite start temperature. At and above the austenite finish temperature (A\textsubscript{f}), the material will have completed its shape memory transformation and will display its super-elastic characteristics.\textsuperscript{18}

Before 2011, the A\textsubscript{f} temperature for the majority of available NiTi instruments was at or below room temperature. As a result, conventional NiTi files were in the austenitic phase during clinical use, showing shape memory and super-elasticity. In 2011, controlled memory (CM) files were introduced by international dental specialist COLTENE. These files are manufactured utilising a unique thermomechanical process that controls the material’s memory, making the files extremely flexible and fatigue-resistant without the shape memory and restoring force of other NiTi files. The A\textsubscript{f} transformation temperature of CM files has been found to be clearly above body temperature. As a result, these files are mainly in the martensitic phase at body temperature.\textsuperscript{19} When the material is in its martensitic form, it is soft, ductile and without shape memory, and can easily be deformed, but will recover its shape and super-elastic properties upon heating over the A\textsubscript{f} temperature. Moreover, a hybrid martensitic microstructure, like that used in the HyFlex CM files (COLTENE), is more likely to have a better fatigue resistance than an austenitic microstructure is. At the same stress intensity, the fatigue crack propagation speed of austenitic structures is much faster than that of martensitic ones. A quantitative analysis based on the model of the fracture process zone showed that the martensite transformation in the shape memory NiTi alloy caused a 47\% increase in the apparent fracture toughness.\textsuperscript{19}
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Very recently, CM thermomechanical processing was combined with an innovative machining procedure for the manufacture of rotary NiTi files. Electrical discharge machining (EDM) results in instruments of increased surface hardness, cutting efficiency and extreme fatigue resistance. In the first published paper evaluating these files, a typical spark-machined peculiar surface was reported and low degradation was observed after multiple canal instrumentations. The authors also found surprisingly high values of cyclic fatigue resistance and safe in vitro use in severely curved canals. In agreement with previous researchers, Pedulla et al. reported higher values of fatigue resistance for HyFlex EDM files (COLTENE) even when compared with reciprocating files made from M-wire.

Unfortunately, most of the available literature on bending stiffness and cyclic fatigue fracture resistance of NiTi rotary or reciprocating instruments concerns studies performed at room temperature. However, room temperature is not a clinically relevant temperature. Current instruments are used at body temperature rather than room temperature. This makes most of the previous studies obsolete and their conclusions cannot be applied in the clinical practice. It seems that the transformation temperature ($A_f$) of rotary or reciprocating NiTi files might alter their clinical behaviour at body temperature. Hulsmann et al. (2019) reported that environmental temperature has a 500% impact on the lifetime of instruments. A transformation temperature near body temperature can result in instruments that appear to be flexible and fatigue-resistant at room temperature; however, at clinically relevant temperatures, the instruments become stiffer and less fatigue-resistant. The $A_f$ of HyFlex EDM was found to be close to 52°C, far above body temperature. A transformation temperature analysis of EDM files revealed the presence of monoclinic martensite B19 structure and rhombohedral R-phase. Therefore

Figs. 4a–h: Tactile-controlled activation technique explained.
EDM instruments are always in a rhombohedral R-phase and martensitic crystallographic state at clinically relevant temperatures. A martensitic structure at body temperature, like HyFlex EDM, will exert superior flexibility and fatigue fracture resistance. The extreme flexibility and fatigue resistance of these files, combined with the lack of restoring force, render them ideal for use in the instrumentation of highly curved and complicated canals.

**HyFlex EDM Max Curve sequence**

EDM made feasible the use of a single-file enlargement approach with rotational movement. Most cases can be shaped quite quickly, effectively and safely by using a single 25/− HyFlex EDM OneFile with short-stroke pecking movements, frequent flute cleaning and irrigation between the strokes. The OneFile has a tip size of 25 with a .08 taper. The taper is a constant .08 in the apical 4 mm of the instruments, but reduces progressively up to .04 in the coronal portion of the instrument. The file has three different cross-sectional zones over the entire length of the working part (rectangular in the apical part and two different trapezoidal cross sections in the middle and coronal parts of the instrument) to increase its fracture resistance and cutting efficiency. Whenever larger apical preparations are required, three finishing HyFlex EDM files of constant taper can be used (40/04, 50/03 and 60/02).

For constricted and obliterated canals, thin and long roots, curved canals of more than 27° and S-shaped canals with a curvature of smaller than 5 mm in radius, single-file EDM shaping is not feasible. For these challenging cases, the HyFlex EDM Max Curve sequence was introduced for use with the TCA technique. With this combination, all those cases can be handled effectively and predictably. The new...
HyFlex EDM Max Curve set includes 15/.03, 10/.05 and 20/.05 files. Under the new concepts of dentinal preservation, flaring can be avoided in order to reduce unnecessary tissue removal from the peri-cervical area. The HyFlex EDM Max Curve sequence can be used with a single-stroke TCA technique. After canal identification and negation, a minimum glide path of 10/.02 should be achieved with stainless-steel hand files before moving to the Max Curve rotary sequence. After making the 10/.02 hand file super loose, the 15/.03 HyFlex EDM file is used to shift the manually achieved glide path to a smooth glide path that all subsequent rotary files can follow. After the 15/.03 file has reached the predetermined length, the 10/.05 HyFlex EDM follows in order to enlarge the middle part of the canal safely without binding the delicate tip. The apical 3 mm of the 10/.05 file functions as a guiding tip (without engaging the canal walls, Fig. 3). The 20/.05 HyFlex EDM file follows as a finishing file to give the final smooth shape. Once a 20/.05 enlargement has been achieved, the canal can be filled with a 20/.05 gutta-percha cone and GuttaFlow bioseal bioceramic sealer (COLTENE). The sequence is easy to remember and works effectively and safely even in tricky situations.

**Tactile-controlled activation**

To minimise file engagement, TCA was developed (Fig. 4a). This instrumentation technique can be defined as the activation of a motionless engine-driven file only after it becomes fully engaged inside a patent canal. TCA utilises file activation only after maximum engagement of the flutes is reached and tactile feedback of the anatomy is felt. Inserting files passively (non-activated) inside the root canals and using CM files that can be pre-bent before file insertion is useful, especially when complicated canal systems are encountered and limited mouth opening hinders canal negotiation and visualisation. TCA can be divided into in-stroke and out-stroke movements.

After accessing the pulp chamber and locating the canal orifices, technical patency to length is confirmed and the canal is enlarged up to 10/.02. The first file of the Max Curve sequence to be used, the 15/.03 file, is mounted on to the handpiece of an endodontic motor and inserted passively inside the canal to the point of maximum frictional resistance (point A, Fig. 4b). The file is activated and pushed apically (in-stroke) until the activated file resists further advancement (point B, Fig. 4c) and withdrawn from the canal. After file withdrawal, the file is inactivated and the flutes are cleaned and checked for any possible deformations. Irrigation and patency confirmation follow. The second time that the same file is inserted passively inside the canal it will bind deeper inside the anatomy (point B, Fig. 4d). Activating the file again the same way will guide the file even closer apically to length (point C, Figs. 4e–g). The work to be done by this file is completed when the file can reach working length (point D, Fig. 4h) without having to activate it. After reaching working length, the second file
of the Max Curve set is used the same way. The delicate apical 2 mm of the 10/.05 file will always remain loose inside the canal, guiding the file through the anatomy without risking engagement and breakage. The 20/.05 that follows will provide the final canal shape to disinfect and obturate the canal.

Instrumentation to larger apical preparations can be achieved the same way to the desired apical instrument width. For challenging cases, as seen in Figures 5 and 6, a 20/.05 enlargement might be ideal in order to balance the clinical disinfection procedures with the risks of damaging the challenging anatomy or separating the instruments. The TCA technique aims at minimising the time of engagement with an activated file by using file activation only when needed for advancement. With this instrumentation technique and the HyFlex EDM Max Curve sequence, most anatomical root canal variations can be enlarged safely.

Conclusion

NiTi files with CM effect are extremely flexible and fatigue-resistant. They can be activated inside the canal and move passively around the curves guided only by anatomy itself. The TCA technique minimises the time files are under engagement. This procedure maintains continuous tactile feedback during instrumentation. For challenging anatomies, special sequences like the HyFlex EDM Max Curve set help clinicians to keep on track.

about

Dr Antonis Chaniotis graduated from the University of Athens’s School of Dentistry in Greece in 1998. In 2003, he completed a three-year postgraduate programme in endodontics at the same school. Since 2003, he has owned a private practice limited to microscopic endodontics in Athens. For the last ten years, he has served as a clinical instructor affiliated with the undergraduate and postgraduate programmes at the Department of Endodontics of the University of Athens’s School of Dentistry. From 2012 to 2014, he was a clinical fellow teacher at the University of Warwick in the UK. He lectures extensively nationally and internationally, and he has published articles in local and international journals. He currently serves as an active member of the Hellenic Society of Endodontology, a certified member of the European Society of Endodontology and an international member of the American Association of Endodontists.

contact

Dr Antonis Chaniotis
140 EL. Venizelou Av.
Stoa Karantinou
176 76 Kallithea
Athens, Greece
antch@otenet.gr

Figs. 6a–d: S-shaped mesial root of a mandibular second molar managed with the HyFlex EDM Max Curve sequence. Pre-op radiograph revealing a deep distal carious lesion (a). Periapical radiograph with 15/.03 HyFlex EDM file taken to working length, revealing the anatomy after the deep distal margin elevation (b). Post-op radiograph after completion of the root canal obturation (c). Post-restoration radiograph (d).