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Nickel–titanium: options and challenges

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Nickel–titanium (NiTi) was developed 40 years ago by Buehler et al [1–3] in the Naval Ordnance Laboratory (NOL) in Silver Springs, Maryland. The symbols of the metals were combined with the place of invention, creating the acronym NiTiNOL, which is used worldwide for this special type of alloy. Using about 55 wt% Ni and 45 wt% Ti and substituting some Ni with less than 2 wt% Co, nearly the same number of Ni and Ti atoms are combined, being reflected in the term *equiatomic*. This alloy is the favorite for use in endodontics (Tables 1, 2) and is commonly referred to as 55 NiTiNOL. Another type is called 60 NiTiNOL and contains about 5% more nickel (see Tables 1, 2). This alloy has been used for some hand files but because of different properties (ie, lower "shape memory effect" and increased heat treatability, together with increasing hardness) it seems to be less useful than the 55 NiTiNOL [4].

NiTi alloys overall are softer than stainless steel, are not heat treatable, have a low modulus of elasticity (about one fourth to one fifth that of stainless steel) but a greater strength, are tougher and more resilient, and show shape memory and superelasticity [4–6]. The latter two properties are the main reasons why NiTi alloys have succeeded in endodontics and some other dental disciplines and are due to a change in the crystal structure. The low-temperature phase is called the martensitic or daughter phase (a body-centered cubic lattice) and the high-temperature phase is called the austenitic or parent phase (hexagonal lattice), which follows the naming of the reactions of stainless steel.

This lattice organization can be altered either by temperature or stress. Although temperature changes are used during the manufacturing process, root canal treatment causes stress to NiTi files and a stress-induced martensitic transformation takes place from the austenitic to the martensitic

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Table 1
Composition of nickel–titanium rotary and hand files following an EDAX-analysis[a]

	Composition				
File type	Ni	Ti	Al	Fe	Co
Machined					
ProFile (Dentsply Maillefer)	54,26	45,42	0	0.04	0.28
Hero 642 (MicroMega)	54,37	45,32	0	0.05	0.26
FlexMaster (VDW-Antaeos)	55,28	44,42	0	0.03	0.27
Hand					
NitiFlex K-File (Dentsply Maillefer)	54,36	45,31	0	0.05	0.25
UltraFlex K-File (Texceed)	59,14	40,40	0	0.18	0.28
Onyx-R-File (Union Broach)	43,65	38,97	16,74	0.33	0.24

[a] EDAX; Energy Dispersive Analysis of X-rays.

Data from Schäfer E. Wurzelkanalinstrumente für den manuellen Einsatz: Schneidleistung und Formgebung gekrümmter Wurzelkanal abschnitte. Berlin: Quintessenz; 1998.

phase within the speed of sound. A change in shape occurs, together with volume and density changes. This ability of resisting stress without permanent deformation—going back to the initial lattice form—is called superelasticity. This quality is not unique to NiTi because CuZn, CuAl, AuCd, and NiNb alloys also show it, but these alloys are less biocompatible [2,4].

The superelasticity 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% [6,7].

Within this range, the so-called "memory effect" can be observed: the NiTi file comes back to its original straight form without showing any sign

Table 2
Properties of nickel–titanium and stainless steel

Property	55 NiTiNOL		60 NiTiNOL cooled from 950°C		Stainless steel
Density (g/cm^3)	6.45		6.71		7.9
Melting temperature (°C)	1310		1125		1500–1550
Hardness					
Vickers	303–362		303		600–610
Rockwell	(30 above TTR)	(17 below TTR)	(30 water-quenched)	(60 furnace cooled)	
Tensile strength (MN/m^2)	827–1172	103–862	945	1062	2000
Yield strength (MN/m^2)	621–793	34–138	Near tensile strength		1600
Modulus of elasticity (10^{-3} MN/m^2)	83–110	21–69	114	114	285×10^3 N/mm^2
Elongation %	1–15	−60	7	—	2

Abbreviation: TTR, transformation temperature range.

—, No information available.

Data from Refs. [4–7].

of lasting deformation. Nevertheless, without any prior notice, a fracture can occur suddenly.

The Vickers hardness number of NiTi is about 300 to 350, far beneath that of stainless steel, which is about 530. Both values are far higher than dentin, however, which has a Vickers hardness number of up to 70 [8], and root canal dentin, which has a value of nearly 30 to 35 [9]. Nevertheless, the surface of NiTi instruments obviously is not homogenous, and Serene et al [10] found that the cutting edges were softer than the core of the instruments. This finding meant a lower cutting efficiency and a higher wear than for stainless steel files and, therefore, a higher frequency of exchange of files. The cutting efficiency of NiTi instruments is not judged uniformly but in the end, it is about one half or two thirds that of stainless steel [11]. Thus, a disadvantage for NiTi hand files is the permanent rotating manner in which modern NiTi files are used in combination with the greater taper: although this increases the cutting ability, the wear increases, which leads some clinicians to maintain that NiTi files are disposable instruments.

Manufacturing

In this context, the manufacturing of NiTiNOL alloys plays a key role for understanding some inherent challenges (for details, see reference [4]). Machining of the original NiTi wire should be conducted at 220 ft/min^{-1} with carbide burs or silicone carbide wheels (stainless steel tool wear was extremely high) under active highly chlorinated cutting oil involving light feeds and slow speeds [4]. Twisting, as it is done with stainless steel K files and K reamers, is impossible due to the superelastic properties and the memory effect. Therefore, machining and grinding is the only way for NiTi. In the very beginning, milling marks with severe surface alterations, rollover of the edges, and inhomogeneities often could be observed, thus leading to

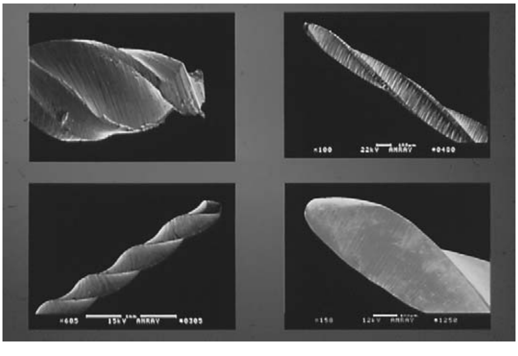

Fig. 1. The surface of the early NiTi files was rough with grooves and roll overs. Quantec (1997) is shown in the upper left panel. ProFile (1997) is shown in the upper right panel. An experimental file (1998) is shown in the lower left panel. Modern surfaces (RaCe) are much smoother, as shown in the lower right panel.

accelerated wear, fatigue, and finally breakage (Fig. 1). Some manufacturers have overcome this problem (Fig. 2). In addition to inhomogeneities and surface alterations, corrosion and resistance to repeated sterilization are issues that must be discussed.

Corrosion and sterilization

The environment of the mouth (body temperature, saliva with its salts and electrolytes, blood) causes corrosion of NiTi alloys [12,13]. Corrosion pits in products rich in titanium were described by some authors [14–16], whereas Edie et al [17] saw no difference in surface characteristics under the scanning electron microscope or in terms of oxygen contact, meaning corrosion. United States Navy tests found that NiTi had good corrosion resistance, good stress corrosion, and performed well in a marine environment [2].

Differences in the effects of sterilization on NiTi alloys also have been fond. Older studies tested orthodontic NiTi wires. One study used dry heat, formaldehyde vapor, and a steam autoclave. The elastic properties, resilience, deflection rate, and surface were unaltered [18]. Another group also saw no clinical differences [19], whereas other researchers observed a higher stiffness, reduced pseudoelasticity, and changes in load and unload [20].

More recent studies on endodontic instruments indicate that there are changes but that they are not seen as clinically relevant [12,21,22]. Dry heat and steam autoclave decreased the flexibility of stainless steel and NiTi files, but the values satisfied International Standards Organization specifications [12]. These results were confirmed in another study with different files in which sterilization altered the bending moment only slightly [22]. Clinical use with sodium hypochlorite (NaOCl) and repeated sterilization "did not lead to a decrease in the number of rotations to breakage of the files" [21].

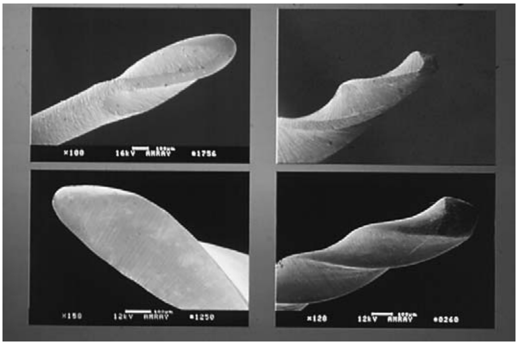

Fig. 2. The tips of most files are more or less rounded. LightSpeed is shown in the upper left panel; GT in the upper right; RaCe in the lower left; and Hero in the lower right., see also Fig. 5.

Another study used spectroscopy to examine the chemical composition of the surface layer and found that repeated heat sterilization altered the superficial structure of the instruments so that the amount of oxygen on the surface was enhanced, therefore reducing the cutting ability of NiTi files [23].

In addition, for NaOCl (the main irrigation solution in endodontics), there is a hint of pitting corrosion after sterilization and exposure to 5% NaOCl [13]. The effect of NaOCl in various concentrations (but without looking at sterilization) was reinvestigated [24]. After 30 to 60 minutes, statistically significant amounts of titanium were dissolved from the tested LightSpeed (LightSpeed Endodontics, San Antonio, Texas) instruments. Such contact times are never reached under clinical conditions and, therefore, are thought to be irrelevant. Nevertheless, in cases in which a clean stand is filled with a solution of NaOCl for disinfection during root canal treatment, a relevant time of more than 30 minutes will easily be reached. A recent study showed that "repeated sterilization under autoclave or exposure to sodium hypochlorite (NaOCl) before sterilization did not alter the cutting efficiency of PVD (physical vapor deposition)-coated NiTi K-files" [25].

Allergies

Nowadays, dentists are asked many questions by their patients. One topic that patients ask about is the allergenic potential of endodontic NiTi-files. Nickel is the most widespread allergen in the industrial nations because of its usage in fashion jewelry and consumer products [26]. Nickel hinders the mitosis of human fibroblasts [26] but NiTi seems to lack this effect [27] and shows good biocompatibility [28]. One explanation is the equiatomic ratio of Ni and Ti.

Chronology of nickel–titanium use in endodontics

When the Gates–Glidden (GG) bur was invented in 1885, rotating instruments in endodontics and dentistry in general were very rare. The first contra angle with a whole circle rotation is attributed to Rollins in 1899—about 1 century ago. Since then, it seems that cavity preparation and endodontics cannot be thought about without the use of modern handpieces and diamond burs; however, "modern" instruments were not developed until the 1930s when Endocursor was designed, 1958 when Racer was introduced, and 1964 when Giromatic was developed. Modern ideas in the 1980s were transformed into the canal finder and canal leader, with the special combination of 90° and an up-and-down filing movement. At that time, sonic and ultrasound devices appeared but never really succeeded. The discovery of NiTi alloys enabled a steadily accelerating development of NiTi files that—first developed and designed for hand instrumentation—enabled a whole range of permanent rotating systems now available in a wide range

Table 3
Chronology and selected data of rotary Nickel–titanium files

Instrument	Year	Cross-section	Taper	Tip
NT Engine	1991	Modified H file	02	Pilot
LightSpeed	1992	U file	00	Pilot
Mity roto	1993	U file	02	Pilot
ProFile	1993	U file	02–06	Pilot
Orifice Shaper	1993	U file	05–08	Pilot
PowerR	1994	U file	02–06	Pilot
Quantec	1996	Modified K file	02–12	Various
GT rotary	1998	U file	04/06–12	Pilot
Hero 642	1999	Modified H file	02–06	Modified active
RaCE	1999	Modified K file	02–10	Pilot
FlexMaster	2000	Modified K file	02–06	Modified active
ProTaper	2001	Modified K file	Multiple/reverse	Modified active
K3	2001	Modified K file	02–10	Pilot
Endostar	2001	Modified K file	02–10	Pilot
NiTi-Tee	2002	Modified S file	02–12	Pilot
K2	2002	Modified Uni file	02–08	Pilot
MFile	2003	Modified K file	02–06	Pilot

of types and brands. The combination of the old idea of 360° rotation with the new technology met with great success, and progress continues to be made, even after 15 years.

The sequence of NiTi files opened with NT engine files by McSpadden and the LightSpeed system by Wildey and Senia [29] and finds its preliminary end today with the MFile by Brasseler (Table 3). Various NiTi systems are described throughout this issue and many studies have been designed to evaluate the advantages and disadvantages of them. A large number of articles can be found when looking on the Internet for NiTi (424) or NiTi and dentistry (221). A complete book on root canal treatment with Ni-Ti instruments has been edited by Quintessence in Germany in 2002 [30] and many scientists and practitioners around the globe focus on this new mechanical approach to shape the root canal.

Over the years, three brands have dominated the discussion, the ideas, and the market: LightSpeed, ProFile, and Quantec, which all share features that are common and widespread in nearly all systems. During the last several years, however, there have been some changes in the fundamental design. A second generation of NiTi instruments, research, and theory has enabled fast development and improvements that are reviewed here.

International standards organization recommendations

For almost a hundred years, instruments for manual preparation of the root canal system have been manufactured in a similar way: there are three main types, namely the reamer, the K file, and the H file. The common feature of all three is that they have a total cutting length of 16 mm and an increase in diameter by 0.02 mm per millimeter. This increase in diameter is termed a *taper* of 2%. For example, an instrument designated as size 25 is 25/100 mm thick at the tip (ie, 0.25 mm). At the end of the cutting edge, it is 16 × 0.02 mm = 0.32 mm thicker (ie, 0.25 mm + 0.32 mm = 0.57 mm).

In addition, the cutting edges are always positioned at equal intervals so that all endodontic instruments of this type are basically designed to be similar to a screw. The cutting edges meet the canal wall at different angles (reamer with an angle of approximately 20°, K files with 40°, and H-files with 60°). In addition, reamers have only around half as many cutting edges as K files, making a reaming motion possible with only a slight tendency for the reamer to screw itself into the canal. K files are considerably more effective than K reamers, although because of the significantly higher risk of screwing themselves into the canal, they must not be turned in the canal more than half a circle (180°). This technique was the standard until the NiTi era began.

Common features of nickel–titanium files

Tip

The tip is mostly rounded to serve as a guide within the canal without cutting at all (Fig. 2; eg, LightSpeed, Quantec LX, System GT). Exceptions are the early Quantec design, which had a sharp cutting tip with 60° or 90° (Fig. 3), the early ProFile, with some sharp edges at the end (Fig. 4, see also Fig. 1), and FlexMaster (Fig. 5) in which the cutting edges go far to the tip.

Cutting egdes

In the beginning, cutting edges had been flattened, named “radial land” (ie, for LightSpeed, ProFile, Orifice Shapers, GT rotary, System GT). This flattening was necessary because every permanent rotating system has the tendency to screw into the canal. To overcome this problem, clinicians could flatten, modify, or shorten the cutting edges and vary the flute height or taper. All of these ideas have been used in one or another systems:

Flattening the edges (radial lands): used in LightSpeed, ProFile, System GT (see Fig. 4).

Modifiying the edges: Quantec (see Fig. 3) and K3 have very complex cutting edges that stay between the flattened and sharp edges and are thought to enhance the cutting ability and combine a big chip space with a strong core.

Shortening the cutting edges: System GT with d0 = 0.20 mm (6.66 mm in GT 0.12, 8 mm in GT 0.10, 10 mm in GT 0.08, and 13.33 mm in GT 0.06), RaCe files with 9 or 10 mm, MFile with 4 to 6.5 mm, and the ultimate reduction of LightSpeed with 0.5 to 1.75 mm (Fig. 6).

Varying the flute height: examples are GT rotary files and System GT (see Figs. 4, 6) or the MFile (see Fig. 6). RaCe finally shows alternating of short twisted with straight areas (see Figs. 5, 6) [31].

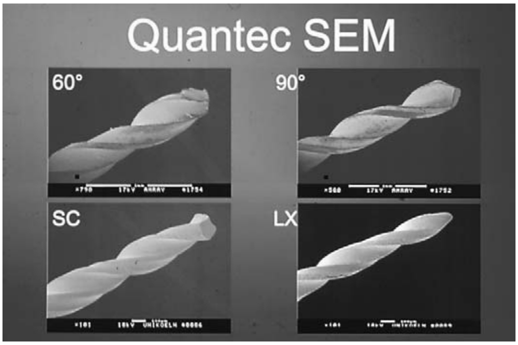

Fig. 3. The Quantec tip has gone through a special development: from a 60° degree tip (*upper left*) and a 90° degree variation (*upper right*) to a shield tip (*lower left*) and a torpedo tip (*lower right*).

Varying the taper: one of the very new ideas of NiTi file development is the increase of the standardized taper, which was 2% normally referring to the International Standards Organization standard (see Table 3). The first systems stayed in this tradition (NT Engine, Mity roto) or created a no-taper variance (LightSpeed), producing parallel walls for the first time. Starting with ProFile, the double, triple, and higher (“greater”) taper pioneered its way. A double taper or taper 0.04 means that with every millimeter of cutting length, the instrument gets bigger by 0.04 mm. A triple taper or taper .06 means that with every millimeter of cutting length, the instrument gets bigger by 0.06mm, and so on. There are not only “even” taper but some systems like Quantec, Orifice Shapers, and ProTaper also have “odd” taper. The ProTaper system (see Fig. 5) defies imagination, having reverse and multiple taper within one file [32,33].

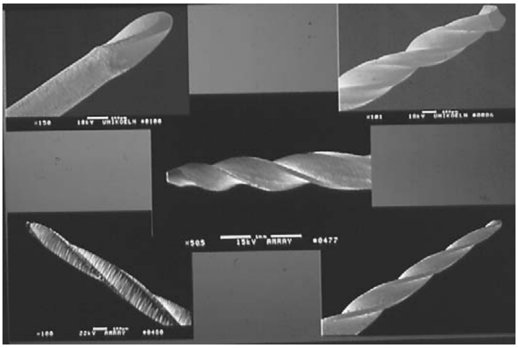

Fig. 4. Many NiTi file brands show flattened cutting edges like LightSpeed (*upper left*), Quantec SC with a complex cutting surface (*upper right*), MFile (notice the change of flute heights; *center*), ProFile (*lower left*), and GT rotary (change of flute heights; *lower right*).

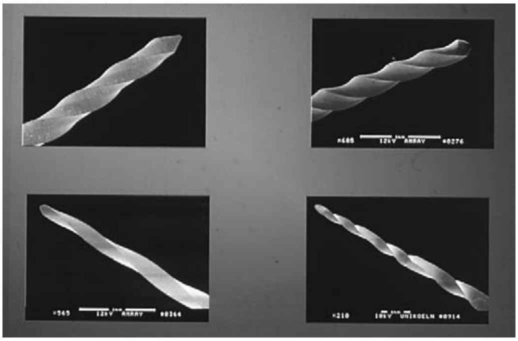

Fig. 5. Recently, a change to sharp cutting edges has been undertaken and some brands show this variability. FlexMaster is shown in the upper left panel; Hero in the upper right; ProTaper in the lower left, and RaCe in the lower right. ProTaper shows a variation of taper and a change from flute height. RaCe exhibits an alternation of twisted and straight areas.

New approaches and challenges

When referring to reverse and multiple taper, some aspects of contemporary file designs have been addressed. By having better ways of manufacturing and grinding NiTi wires and calculating mathematic models of stress [34], some manufacturers began to produce sharp cutting edges (eg, Flexmaster, ProTaper, Hero 642). This sharp cutting edge results from a triangular cross-section (eg, FlexMaster, ProTaper) [32,35].

To replace the old-fashioned but effective GG-burs, many manufacturers designed similar NiTi instruments. The Orifice Shapers from Dentsply Maillefer are six instruments with high taper (5%–8%) and a short working end. File 1 from Quantec, used for crown down, is a size 25 0.06, being only 19 mm from tip to handle and exactly the same as file 8, used up to total length with size 25 0.06, but being 25 mm length. The IntroFile from VDW-Antaeos

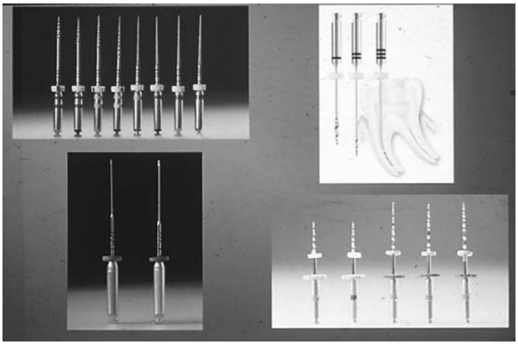

Fig. 6. A shortening of cutting edges is one way to decrease the tendency of NiTi files to screw into the root dentin. GT rotary files are shown in the upper left panel; MFile in the upper right; LightSpeed in the lower left, and RaCe in the lower right.

(München–D) has taper 11% and a tip diameter size 22. The GT rotary files and System GT also can serve as crown down instruments. The obvious advantage of all these approaches is that the tip diameters are mostly smaller than the smallest GG-bur, with size 50 thus needing a comfortable size of the canal entrance, which cannot be expected anyway. The higher flexibility of NiTi is another point. Another way to overcome this problem has been developed by FKG, the manufacturer of RaCe files. FKG offers stainless steel files for crown down (0.08 taper/size 35 and 0.10 taper/size 40).

This discussion reflects some of the aspects that have arisen with the variation of NiTi file designs. A highly interesting monograph dealing with this subject in extenso is the book *Endodontic Instrumentation: Essentials for Expertise* by McSpadden [36], which will be published soon.

This discussion has been closely related to the invention of specific endodontic motors with torque control. Fatigue, however, is an unsolved problem and another challenge for NiTi manufacturers. The SET identity—a special box that calculates the cycles and life span of NiTi files—may provide an answer (see Fig. 5).

A last aspect under discussion is the enhancement of the surface hardness of NiTi files. As previously discussed, the NiTi alloy is a strange alloy that barely can be machined, resulting in a poor surface texture with roll overs and grooves. Therefore, the possibilities of coating the surface is discussed in the literature [25,37–41].

One approach is ionic implant and thermal nitridation [42]. Lee et al [37] found that the implantation of 4.8×10^{17} per ion/cm^2 of boron increased the surface hardness. Another approach is the thermal nitridation for 480 minutes at 500°C or ionic implantation with 150 keV nitrogen ions at doses of 1.0×10^{17} per ion/cm^2. The wear resistance of ProFiles was enhanced with both approaches. Regular ProFiles showed a decrease in cutting ability after 80 seconds, whereas the ionic implantation and thermal nitridation showed no loss in cutting ability over 240 seconds. Finally, a physical vapor deposition of TiN also increased the cutting ability [43] and helped the files to withstand repeated sterilization or exposure to NaOCl [25].

Summary

A large number of studies have dealt with various aspects of NiTi files, such as the physical and chemical characteristics of NiTi alloys and the original files available, the biologic acceptance and allergies, the enhancement of cutting ability and file design using plastic block studies, clinical trials, the question of torque and fatigue, special motors, scanning electron microscope studies for testing the cleaning and shaping ability, student studies, and many others (for review, see reference [30]). There are some leading scientists and companies that are driving the development of NiTi technology. Side developments of endodontics such as different irrigations and lubricants, new filling methods, apex locators in combination with high-tech endodontic motors, and others have caught the "wave of technisation." In this way, endodontics is a mirror of the world: some dentists and scientists defend their old bastions and argue to stay with hand instrumentation, claiming the ever heard warnings that there is nothing better than the "good old times" and a highly advanced filing technique by hand; others have thrown away all their old instruments and former ways of proceeding, and are "riding the wave."

Of course, permanent rotating instruments only can create round holes, and canals are not really round all over.

Of course, circumferential filing is not possible or only restrictedly possible with NiTi files.

Of course, there is evidence that NiTi files lead to a more centered canal form that is very close to the original but have a tendency of straightening the canal when the instrument is left too long within the canal.

Of course, a complete instrumentation and herewith cleaning of canal walls cannot be achieved by mechanical means; neither with stainless steel hand files, NiTi hand files, or any NiTi rotary system.

Of course, every success with dental performances mainly depends on the dentist and secondly comes from the material.

In this context, the large studies in Glasgow on plastic blocks by Dummer and colleagues [4] and in Göttingen on extracted teeth (see review in [30]), looking for straightening, working time, blockages, loss of working length, fractures, and perforations found that there are differences between brands and that some do not proceed as well as others but overall, "independent from the study design or observer, the results for the most systems differed only slightly and were highly constant" [30].

Some universities in Germany (ie, Hannover and Köln) have changed their endodontic concept by totally changing from hand instrumentation to NiTi files with endomotors for the past 3 years, with great success [44,45]. The combination of the use of contemporary available modern devices and files with a solid base of anatomic and biologic knowledge will lead to a predictable higher quality of root canal treatment on a broader basis, thus helping to preserve more teeth for more years in the mouth.

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