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Evaluation of rotary root canal instruments *in vitro*: a review



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Key words *instrument separation, root canal preparation, rotary nickel-titanium instruments, shaping ability, transportation*

In the last decade, rotary nickel-titanium (NiTi) instruments have become increasingly popular for preparing root canals. Therefore, the aim of the present article is to review the literature on *in vitro* evaluation of rotary root canal instruments. The focus is on studies of shaping and cleaning ability, safety and working time. The use of NiTi instruments produced sufficient cleanliness with acceptable preservation of the root canal anatomy. Both centring ability and decreased straightening of root canals is superior with NiTi instruments compared with the manual technique using stainless steel instruments. However, the apical part of the root canal showed similar or fewer remnants of debris after manual instrumentation. These aspects highlight the demand for an efficient irrigation combined with mechanical preparation of the root canal. Additionally, the use of a torque-controlled device and constant speed control is recommended to reduce the risk of instrument fractures. It can be concluded that appropriate handling of engine-driven NiTi systems in combination with sufficient (antimicrobial) irrigation facilitates successful endodontic treatment.

■ Introduction

The preparation of the root canal system is essential for a successful outcome in root canal treatment¹. Mechanical debridement of the root canals is meant to eliminate vital and necrotic tissues from the root canal system, along with removal of infected dentine. Canal therapy also creates space to facilitate disinfection by irrigants and medicaments, and an optimal shape for three-dimensional obturation. An adequate coronal restoration and a microbial-tight root canal filling are necessary to prevent reinfection.

Thus, mechanical preparation and chemical disinfection are commonly considered together and referred to 'chemo-mechanical preparation'.

The development of rotary nickel-titanium (NiTi) instruments is considered to be an important innovation in the field of endodontics. During the last few years, several new instrument systems have been introduced and the number of users of these systems has increased considerably. The purpose of the present article is to review the literature published on the *in vitro* evaluation of rotary instruments used for root canal preparation. The focus is on shaping



and cleaning ability, safety and working time. Studies were identified by searches of PubMed and Scopus with the terms 'rotary nickel-titanium instruments', 'root canal preparation, 'fracture', 'transportation' and 'shaping ability'. Papers published up to January 2007 were selected, and the relevant references chosen.

■ History of NiTi rotary instruments

More than 100 years ago, the first endodontic handpiece was developed with the aim of reducing the treatment time and simplifying the preparation procedure. Furthermore, it was hoped the efficiency and accuracy of endodontic procedures would be improved. As early as 1889, William H Rollins used specially designed needles, which were mounted in a rotary handpiece. A new era in handpiece design began with the introduction of the Canal Finder System (now distributed by S.E.T., Gröbenzell Germany) by Guy Levy in 1984². This was the first endodontic handpiece with a partially flexible motion. Further examples of handpieces with modified working motions were the Excalibur handpiece (W&H, Bürmoss, Austria), designed to function with laterally oscillating instruments, and the Endoplaner (Microna, Spreitenbach, Switzerland), which used an upward filing motion³.

NiTi alloys were first developed in 1962 and later commercialised under the trade name Nitinol, an acronym for Nickel Titanium Naval Ordnance Laboratory. Nitinol is one of the main three types of shape memory alloys, also known as memory metals. Its remarkable properties led to an increasing range of applications in medicine and especially dentistry. In 1988 this alloy found its way into endodontics when Walia et al⁴ introduced Nitinol root canal hand files.

The NiTi alloys used for manufacturing root canal instruments consist of approximately 55% (w/w) nickel and 45% (w/w) titanium, and is given the generic name 55-Nitinol. NiTi files have a two to three times higher elastic flexibility in bending and torsion as well as superior resistance to corrosion compared with stainless steel files⁵.

One of the main characteristics of this alloy is 'pseudo-elasticity' or 'super-elasticity'. The NiTi alloy exists in two different crystallographic forms, altering

the type of atomic bonding, causing unique and significant changes in mechanical properties. Crystallographic changes at high temperature result in the formation of austenite, and at low-temperature, martensite. The transition from the austenitic to martensitic phase can occur as a result of temperature and stress, e.g. during root canal preparation. After the release of stresses, the metal returns to the austenitic phase, and the file reverts to its original shape. This phenomenon is called stress-induced thermoelastic transformation. Due to its pseudoelastic properties, this material can survive deformation without reaching the elastic limit, thus returning to its original shape⁶.

■ NiTi rotary systems

Currently, there are about 20 different NiTi systems on the market. Individual design features affect the performance of NiTi rotary instruments. Important mechanical features include the variability of taper (constant, increasing or decreasing) and the rake angle (direction of the cutting edge). The latter can be negative, neutral or positive. Other features are cross-sectional geometry (e.g. triangular, triple helix, asymmetrical, S-shape, U-flute design), tip configuration (a rounded and non-cutting tip, cutting tip), design of blades (e.g. radial lands), helical angle (angle between the cutting edge and the long axis of the file) and pitch (distance between cutting edges). These design features influence flexibility, cutting efficiency and safety. In this review of *in vitro* studies, commonly used NiTi rotary systems are summarised (Table 1).

■ LightSpeed system (LightSpeed Technology, San Antonio, TX, USA)

The name LightSpeed is meant to refer to simple handling with concomitant rapid rotation speed. The complete system consists of 22 instruments, ranging from ISO 20 to 100. Additionally, instruments with half sizes between ISO 20 and 60 are available. Each instrument consists of a short cutting head and a smooth flexible non-tapered shaft. This system was originally designed to improve the flexibility of stainless steel hand files⁷. Depending

**Table 1** Overview of the described NiTi systems (continued on the next two pages).

System	Radial lands	Cross-section	Rake angle	Rotation speed (rpm)	No. of sequences
LightSpeed (LightSpeed Technology, San Antonio, TX, USA)	Yes	U-shape, three edges	Neutral	750–2000	ISO 20 to 100
Hero 642 (Micro-Méga, Besançon, France)	No	Triple helix, three edges	Positive	300–600	<i>Blue sequence (easy canals)</i> taper .06 size 30 taper .04 size 30 taper .02 size 30 <i>Red sequence (average difficulty)</i> taper .06 size 25 taper .04 size 25 taper .02 size 25 taper .04 size 30 taper .02 size 25 <i>Yellow sequence (difficult canals)</i> taper .06 size 20 taper .04 size 20 taper .02 size 20 taper .04 size 25 taper .02 size 25 taper .02 size 30
ProTaper (Dentsply Maillefer, Ballaigues, Switzerland)	No	Convex triangular, three edges	Positive	250–350	taper .02-.11 size 17 S1 taper .03-.19 size 19 SX taper .02-.11 size 17 S1 - WL taper .04-.11,5 size 20 S2 - WL taper .07 size 20 F1 - WL taper .08 size 25 F2 - WL taper .07 size 30 F3 - WL
GT-rotary system (Dentsply Maillefer, Ballaigues, Switzerland)	Yes	U-flute, three edges	Neutral	150–300	<i>GT20 (small canals)</i> taper .10 size 20 taper .08 size 20 taper .06 size 20 taper .04 size 20 - WL <i>GT30 (medium canals)</i> taper .10 size 30 taper .08 size 30 taper .06 size 30 taper .04 size 30 - WL <i>GT40 (large canals)</i> taper .10 size 40 taper .08 size 40 taper .06 size 40 taper .04 size 40 - WL <i>Accessory Files</i> taper .12 size 50 taper .12 size 70 taper .06 size 20 taper .04 size 20 - WL
K3 (SybronEndo, West Collins, CA, USA)	Yes	Asymmetrical, three edges	Positive	200–300	<i>K3 Procedure Pack</i> taper .10 size 25 taper .08 size 25 taper .06 size 40 taper .06 size 35 taper .06 size 30 taper .06 size 25 or taper .10 size 25 taper .08 size 25 taper .04 size 40 taper .04 size 35 taper .04 size 30 taper .04 size 25

**Table 1** Overview of the described NiTi systems (continued).

System	Radial lands	Cross-section	Rake angle	Rotation speed (rpm)	No. of sequences
K3 (continued) (SybronEndo, West Collins, CA, USA)	Yes	Asymmetrical, three edges	Positive	200–300	<i>K3 G-Pack</i> taper .12 size 25 taper .10 size 25 taper .08 size 25 taper .06 size 25 taper .04 size 25 taper .02 size 25 <i>K3 VTVT Packs</i> taper .10 size 25 taper .08 size 25 taper .06 size 35 taper .04 size 30 taper .06 size 25 taper .04 size 20
ProFile (Dentsply Maillefer, Ballaigues, Switzerland)	Yes	U-flute, three edges	Negative	150–300	<i>Narrow canals</i> taper .06 size 40 Orifice Shaper taper .06 size 30 Orifice Shaper taper .06 size 25 ProFile.06 taper .06 size 20 ProFile.06 taper .04 size 25 ProFile.04 taper .04 size 20 ProFile.04 - WL taper .04 size 25 ProFile.04 - WL <i>Medium canals</i> taper .07 size 50 Orifice Shaper taper .06 size 40 Orifice Shaper taper .06 size 30 ProFile.06 taper .06 size 25 ProFile.06 taper .04 size 30 ProFile.04 taper .04 size 25 ProFile.04 - WL taper .04 size 30 ProFile.06 - WL <i>Large canals</i> taper .08 size 60 Orifice Shaper taper .07 size 50 Orifice Shaper taper .06 size 35 ProFile.06 taper .06 size 30 ProFile.06 taper .04 size 35 ProFile.04 taper .04 size 30 ProFile.04 - WL taper .04 size 35 ProFile.04 - WL
RaCe (FKG Dentaire, La-Chaux-de-Fonds, Switzerland)	No	Triangular .20/20 - square	Positive	300–600	<i>Easy RaCe (simple, medium canals)</i> taper .10 size 40 taper .08 size 35 taper .06 size 25 taper .04 size 25 taper .02 size 25 - WL or taper .08 size 35 taper .10 size 40 taper .02 size 25 - WL taper .04 size 25 - WL taper .06 size 25 - WL



Table 1 Overview of the described NiTi systems (continued).

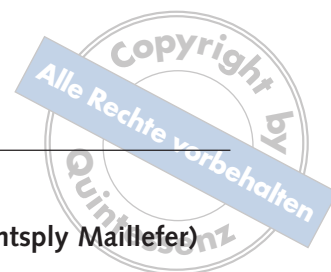
System	Radial lands	Cross-section	Rake angle	Rotation speed (rpm)	No. of sequences
RaCe (continued) (FKG Dentaire, La-Chaux-de-Fonds, Switzerland)	No	Triangular .20/20 - square	Positive	300–600	<i>Xtreme RaCe (difficult canals)</i> taper .10 size 40 taper .08 size 35 taper .02 size 15 - WL taper .02 size 20 - WL taper .02 size 25 - WL
FlexMaster (VDW, Munich, Germany)	No	Convex triangular, three edges	Positive	150–300	<i>Narrow canals</i> Intro File taper .06 size 20 taper .04 size 30 taper .04 size 25 taper .04 size 20 taper .02 size 20 - WL taper .02 size 25 - WL taper .02 size 30 - WL taper .02 size 35 - WL <i>Medium canals</i> IntroFile taper .06 size 25 taper .06 size 20 taper .04 size 30 taper .04 size 25 taper .02 size 25 - WL taper .02 size 30 - WL taper .02 size 35 - WL <i>Large canals</i> IntroFile taper .06 size 30 taper .06 size 25 taper .06 size 20 taper .04 size 30 taper .02 size 30 - WL taper .02 size 35 - WL
Mtwo (VDW, Munich, Germany)	No	S-shape, two edges	Positive	Not specified	taper .04 size 10 - WL taper .05 size 15 - WL taper .06 size 20 - WL taper .06 size 25 - WL taper .05 size 30 - WL taper .04 size 35 - WL taper .04 size 40 - WL (taper .07 size 25 - WL – optional, depending on the obturation technique)

on size, the short cutting head is 0.25–1.75 mm long. Furthermore, the files have a non-cutting pilot tip with blades of U-design, radial lands and a neutral rake angle. The diameter of the shaft increases according to the ISO size. Due to the short cutting head this system tends to produce a round parallel shape. Therefore, sufficient conicity can only be achieved by using numerous instrument sizes in a step-back sequence⁸. Since 2005, further developments of LightSpeed instruments, called LSX, have been introduced. The number of files has also

been reduced to 12 instruments, and half sizes are no longer available.

■ Hero 642 (Micro-Méga, Besançon, France)

Hero 642 is an acronym for 'High elasticity in rotation', and the numbers 642 represent the varying tapers of 6%, 4% and 2%. A complete set consists of 12 files with varying ISO sizes, tapers and lengths of cutting segments. Compared with other rotary NiTi



systems, Hero files have no radial lands but have a triple helix cross-section with three equally spaced cutting edges and a positive rake angle. In clinical practice the system works in a crown-down manner and is divided into three preparation sequences according to canal curvature.

The newer Hero Shaper rotary NiTi system includes 12 instruments and the preparation sequence has been changed. The variable pitch should allow more effective removal of debris. As for the preparation sequence, the number of files varies between two, three and four instruments with a conicity of 4% and 6% respectively.

■ ProFile (Dentsply Maillefer, Ballaigues, Switzerland)

The ProFile NiTi rotary instrument system was introduced in 1996. There are now four types of instrument: ProFile Orifice Shaper, ProFile .06, ProFile .04 and ProFile .02. The instruments are used in a crown-down manner and three different preparation sequences are selected according to the width of a root canal. All the files have the same cross-sectional geometry, a negative rake angle, and a non-cutting pilot tip (Fig 1). Furthermore, these instruments have three radial lands separated by three U-shaped flutes, providing space for debris accumulation. In addition, a parallel core should enhance flexibility. Each file should not be used for more than 5 to 10 seconds, using a gentle 'in-and-out' motion.

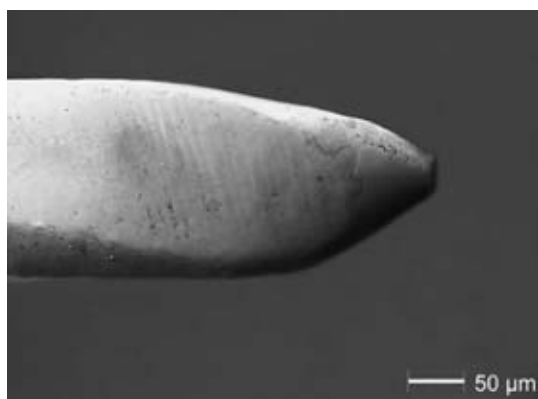


Fig 1 SEM photograph of a ProFile demonstrating its non-cutting pilot tip.

■ GT rotary system (Dentsply Maillefer)

The GT rotary system was introduced in 1998. GT means 'Greater Taper' rotary instruments. The new System GT, available since 2001, consists of three different instrument sequences, GT20, GT30 and GT40, according to the ISO size and with varying taper (10%, 8%, 6% and 4%). In addition, GT accessory files are available for coronal preflaring. These files have a taper of 12%, and variable tip sizes (35, 50 and 70). The instruments are selected according to canal anatomy: small canals, GT20; medium canals, GT30; large canals, GT40. They are used in a crown-down manner. System GT uses the files in a larger-taper to smaller-taper sequence. The instruments have three uniformly spaced U-shaped flutes, a non-cutting pilot tip, radial lands and a neutral rake angle. The varying pitch and a shortened handle of 13 mm are other design characteristics.

■ RaCe (FKG Dentaire, La-Chaux-de-Fonds, Switzerland)

The RaCe system was introduced in 1999. RaCe is an abbreviation for 'Rotary with alternating Cutting edges'. Two different instrument sets are available; the Easy RaCe set for the treatment of simple and medium canals and the X^{trème} RaCe set for the enlargement of difficult curved canals. Each set consists of five NiTi files and includes two 19 mm long, highly tapered PreRaCe for coronal shaping, and three 25 mm long, less tapered RaCe for apical finishing. The Easy RaCe kit may be used in two ways: enlargement in crown-down or in a step-back manner. In contrast, the X^{trème} RaCe files can only be used with step-back technique. RaCe instruments are available in sizes from ISO 15 to 60 with various tapers of 2%, 4%, 6%, 8% or 10%. Additionally, there are two PreRaCe stainless steel files that have a significantly higher cutting performance than NiTi files. RaCe files are characterised by a triangular cross-section, apart from the .02 taper ISO 20 files, which have a square cross-section. Both have a large debris space. The cutting edges show short, twisted segments alternating with straight segments in order to avoid the screwing effect (Fig 2). Furthermore, the files are electrochemically polished to improve resistance to corrosion and fatigue. A short, 12 mm



long handle allows for better access to posterior teeth. Recently, the new BT RaCe system has been introduced by combining the previous two sets.

■ FlexMaster (VDW, Munich, Germany)

FlexMaster instruments are characterised by a convex triangular cross-section with three equally spaced cutting edges, which are similar to the K-type blade, and have a negative rake angle. All instruments have flattened, non-cutting tips. The instrumentation sequence for the FlexMaster system can be modified according to the degree of root curvature and the diameter of the root canal. In curved or narrowed canals, the files with greater taper are designed to initially enlarge the coronal and middle portion of the canal. The 2% tapered files are used to finish the apical area and to blend the apical with the coronal preparations. ISO size 20, 25 and 30 instruments have three different tapers (2%, 4% and 6%). ISO size 35 to 70 are only available as a 2% taper.

■ ProTaper (Dentsply Maillefer, Ballaigues, Switzerland)

The ProTaper system was introduced in 2000. The ProTaper system consists of three shaping and three finishing files. The three shaping files (Auxiliary Shaper [SX], Shaper 1 [S1] and Shaper 2 [S2]) are for coronal preflaring following a crown-down manner. Further instrumentation is performed using the three finishing files (F1 to F3).

The file SX (ISO size 19) has a progressive taper (3% to 19%), whereas the two shaping files (ISO size 17 and 20) have tapers ranging from 2% to 11%, and from 4% to 11.5% respectively. Finally, the three finishing files are ISO size 20, 25 and 30 with decreasing taper (F1, 7% to 5.5%; F2, 8% to 5.5%; F3, 9% to 5%). Five of the six instruments have a convex triangular cross-sectional design. The convex lateral surface of F3 is eroded to increase its inherent flexibility. All instruments have blades close to the non-cutting pilot tip (Fig 3). The flute design combining multiple taper within the shaft is aimed at reducing the contact area between the instrument and the canal wall. Therefore, frictional and torsional loading should be reduced. The debris space increases from tip to shaft, in order to facilitate the removal of dentine and debris. Compared with other rotary instruments, the shaft is 15% shorter in order to facilitate access to posterior teeth. In 2006, the Protaper Universal was introduced by adding two new finishing files, F4 (ISO size 40) and F5 (ISO size 50), for apical preparation.

■ K3 (SybronEndo, West Collins, CA, USA)

K3 files are available in different treatment sequences, each including six files in sizes 15 to 60 with three different tapers (2%, 4% and 6%). In addition, there are two Orifice Openers (8% and 10%) for coronal preflaring. The K3 file has radial lands in combination with a slightly positive rake angle and a flattened non-cutting tip (Fig 4). The cross-section of

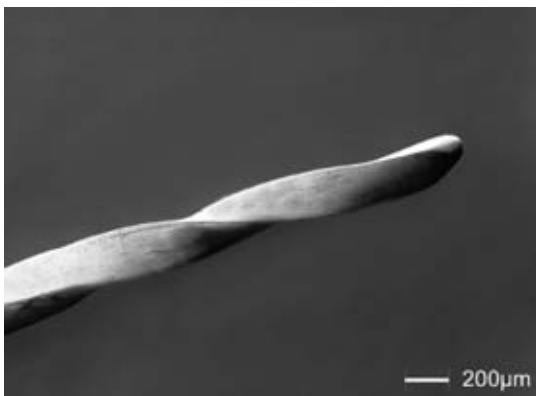


Fig 2 SEM photograph of the cutting surface of a RaCe instrument.

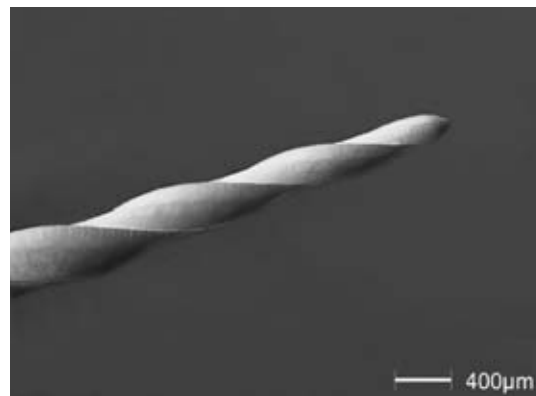


Fig 3 SEM photograph of a ProTaper instrument showing a non-cutting flattened tip with sharp cutting edges near to the pilot tip and intra-blade space to accommodate debris.

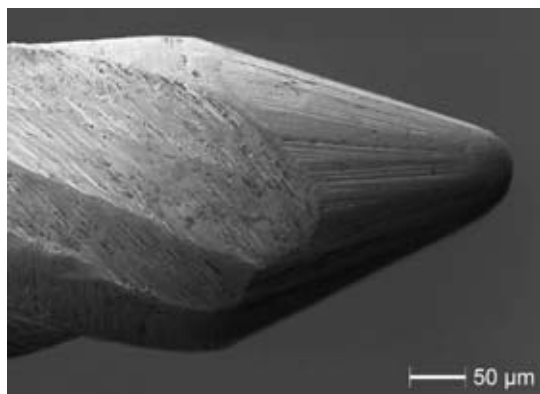


Fig 4 SEM photograph of a K3 instrument with a non-cutting pilot tip and radial lands.

the K3 file is asymmetrical⁹, and the peripheral blade relief has two functions: 1) to increase the peripheral mass in order to prevent file fractures; and 2) to minimise the contact area between the radial lands and the canal wall to reduce frictional resistance. The variable helical angle and a varying core diameter facilitate effective transportation of debris out of the root canal. K3 instruments are used in a crown-down manner with a gentle 'in-and-out' motion.

■ Mtwo (VDW, Munich, Germany)

Mtwo instruments have been available since 2005. The Mtwo system includes eight files with tapers ranging from 4% to 7%, and sizes from ISO 10 to 40. They have an S-shaped cross-sectional design and a non-cutting safety tip. These files are characterised by a positive rake angle with two cutting edges in order to cut dentine effectively. Mtwo instruments have an increasing pitch from tip to shaft to eliminate 'screwing' and binding in continuous rotation. Furthermore, the transportation of debris towards the apex is reduced. All the instruments are used at working length.

■ Clinical requirements

It is necessary to consider various parameters when evaluating the clinical performance of rotary NiTi systems. Important requirements for root canal instruments are shaping and cleaning ability, safety and preparation time.

The preservation of the original canal curvature is a major consideration with regard to shaping ability of

rotary instruments. The prepared canal should have a continuously tapering form¹. The potential formation of 'ledges', 'elbow' and 'zip'^{10,11}, and canal straightening by rotary instruments are also of interest.

In practice it is not always possible to assess the cleanliness of the root canal properly. It can be difficult to detect uninstrumented canal walls, remnants of vital or necrotic pulp tissue, and the formation of smear layer. The cleanliness of a prepared canal is the result of a combination of mechanical and chemical debridement. Cleanliness is often evaluated using SEM (scanning electron microscope) on longitudinal or horizontal sections of extracted teeth¹²⁻¹⁷.

The safety of instruments relates to instrument fractures, perforation, and potential for apical blockages. The preparation time is also important. Access cavity preparation, location and initial coronal enlargement of the root canal are, often, more time-consuming compared with instrumental enlargement. Handling and ease of use of a rotary NiTi system should also be considered.

Due to varying experimental set-ups and the parameters investigated, a direct comparison of the results are difficult. Some studies used simulated root canals in resin blocks¹⁸⁻²². However, there are differences compared to natural teeth with regard to hardness, size of resin chips and canal morphology. Other studies have used extracted natural teeth^{12,23-25}; the number of specimens and the type of teeth studied varied. In addition, the rotary systems evaluated were used in different ways, and the numbers of files were also different.

■ Preparation time

The evaluation of the preparation time should reflect the efficiency of a system and its clinical suitability. Studies that investigated the preparation time of various NiTi systems used different treatment sequences and number of files. Also, the preparation time is dependent on the technique and operator experience.

In some studies, the preparation time is the total time taken for files to work inside the canal^{19,26,27}. Other studies evaluating the preparation time measured the active instrumentation time as well as time for changing instruments and irrigation, resulting in considerably higher values^{12,14,15,18,20-22,28}.



A recently published study investigated five different rotary NiTi systems and the manual technique using Hedström files¹⁸. The 'preparation time' was total instrumentation time, irrigation time and changing instruments time. Results indicate that the FlexMaster system required the most time (mean 8.14 min) to prepare a root canal. More rapid preparation was reported for ProFile (5.08 min), followed by GT rotary (4.17 min), which was significant slower than ProTaper (3.46 min), and the RaCe instruments took the least time (3.18 min). The preparation time of the Hedström files was between RaCe and ProTaper files, but no significant difference was demonstrated. These results are supported by another study reporting a shorter preparation time for ProTaper compared with GT rotary and ProFile¹⁹.

Various studies report that RaCe instruments allow faster preparation than ProTaper, or that no significant differences were found^{13,18,21,24,27}. These findings differed according to the number of RaCe instruments used. It is possible that the design similarities between ProTaper and RaCe systems, based on a triangular cross-section, are important.

An evaluation of six different rotary NiTi systems and hand preparation using stainless steel K reamers, identified three groups of instruments according to preparation time²⁴. Compared with K3, both FlexMaster and System GT needed significantly less working time, whereas Hero 642, RaCe and ProTaper were much slower. All NiTi instruments prepared canals significantly faster than hand preparation. K3, RaCe and Mtwo were evaluated in a two-part study. The preparation time with Mtwo was significantly shorter than with K3 and RaCe^{12,20}.

Root canal preparation using stainless steel hand instruments is influenced by operator experience and technique. Consequently, the literature comparing hand preparation and rotary NiTi instruments showed huge variations in results and are not comparable with regard to preparation time^{14,15,18,22,24,28,29}.

■ Safety

■ Fractures

Torsional fractures or cyclic flexural fatigue are possible reasons for separation of rotary NiTi

instruments³⁰. If the tip or any other part of the instrument is locked in a canal while the shaft continues to rotate, torsional fractures may occur. In this case, the elastic limit is exceeded, resulting in plastic deformation followed by fracture. Torsional fractures are often characterised by macroscopic evidence of plastic deformation (e.g. unwinding [the cutting spirals unravel], straightening, reverse winding [the twist direction of the cutting spirals is reversed] or twisting)³⁰. Cyclic flexural fatigue is caused by mechanical loading and metal fatigue, and there is no macroscopic evidence of plastic deformation³⁰.

The reasons for fractures of rotary NiTi instruments are complex and multifactorial. They are related to instrument design, manufacturing process, canal configuration, applied force during instrumentation, preparation technique, number of uses, and operator's skills and experience. In practice, cyclic metal fatigue is a more important cause of instrument fracture. Repeated bending of instruments in curved canals causes metal fatigue, leading to instrument fracture³¹.

The degree of canal curvature is an important factor for metal fatigue of instruments³¹⁻³³. The likelihood of fatigue fracture increases significantly as the angle of canal curvature increases³¹. It has also been reported that instrument fracture occurs most frequently at the point of maximum flexion of the shaft, which often corresponds to the midpoint of the canal curvature³³. In addition, fatigue resistance is affected by instrument design, inversely proportional to the diameter and degree of instrument taper^{32,34}. Consequently, instruments with greater taper and diameter have a reduced lifespan due to cyclic fatigue³⁴.

Resistance to torsional fractures increases as the diameter of the instrument increases³⁴. Rotary NiTi systems are designed with different cross-sections to improve cutting efficiency and resistance to fatigue. The cross-sectional design's main effect is on the bending properties and the distribution of bending stresses of the instruments. Bending moments are inversely proportional to the cross-sectional area^{35,36}. A high cross-sectional area will have a higher resistance to bending and a lower flexibility. Mathematical calculation of corresponding cross-sectional areas of triple-helix files (e.g. Hero 642) and triple-U files (e.g. ProFile) showed a 30% greater area for the triple helix compared with triple-U files.



Therefore, the triple helix design offers lower and more uniformly distributed stresses. However, ProFile demonstrated a higher fatigue resistance compared with Hero files. This may be due to the lower flexibility of Hero files because of the greater cross-sectional area and a higher bending moment³⁷. It has also been reported that a concave cross-sectional design, such as ProFile, is more flexible than the convex ProTaper design. However, the ProTaper system has lower and better distributed stresses compared with the ProFile system, which might affect the long-term fatigue resistance of this system and possibly fracture resistance³⁸.

Cross-sectional configuration is not the only aspect affecting fatigue resistance. The K3 rotary system, for example, is significantly stiffer than other rotary systems³⁵. A high fatigue resistance has been shown for K3 files^{39,40} and this could be connected to the variable core diameter and the presence of radial lands. Fatigue resistance can also be affected by the depth of the flutes and the number of spirals per unit length^{41,42}.

Torque-controlled motors were introduced with the aim of reducing the risk of instrument fracture⁴³. These motors work at a constant rotation speed and set torque. Common features are auto torque stop, auto torque reverse, speed control and programmed file sequences. The motors have individually adjusted torque limits for each file. Consequently, the rotating instrument is kept below the elasticity limit without exceeding an instrument's specific torque limit⁴⁴, which is dependent on the design and taper of the instrument³⁵.

The fracture rate of rotary NiTi instruments can be reduced by creating a glide path for the instrument tip by manual preflaring^{45,46}. Furthermore, the preparation sequences of instruments have an effect on torsional and cyclic fatigue. Therefore, an instrumentation sequence with various tapers seemed to be safer than a sequence that uses only a single taper, although using various tapers requires more instruments⁴⁷. Cyclical axial motion can also significantly extend the lifespan of rotary files due to reduction in bending stresses⁴⁸.

It has been reported that prolonged clinical use of rotary NiTi instruments significantly reduces their flexural fatigue resistance^{43,49,50}, but other studies found no increased incidence of fracture for

instruments used for up to 10 times^{51,52}. It can be concluded that the number of times rotary NiTi instruments are used before fatigue will depend on several variables, including instrument properties, canal morphology and operator skills.

Machined NiTi instruments often exhibit an irregular surface, characterised by milling grooves, multiple cracks, pits and areas of metal rollover⁵³⁻⁵⁵. Instruments with greater taper offer more surface irregularities than smaller ones, probably due to their more complex manufacturing process⁵⁵. These defects may act as areas of stress concentration and crack initiation during clinical use⁵³.

Electropolishing of NiTi instruments has been introduced by some manufacturers to improve the surface profile (e.g. RaCe) and reduce the number and extent of surface defects. A recent study reported that electropolished instruments survive a higher number of cycles before fracture than non-electropolished instruments⁴⁰.

■ Cleaning ability

The ability to clean the root canal system effectively depends on both instrumentation and irrigation. The primary purpose of irrigation is to flush out loose debris, and remove organic and inorganic material from the root canal system. Sodium hypochlorite (NaOCl) is a widely used irrigant. It is not effective in removing inorganic smear layers, but has bactericidal properties and the ability to dissolve organic tissue^{56,57}. A combination of ethylenediaminetetraacetic acid (EDTA) and NaOCl has been reported to be suitable for removing both the inorganic smear layer and organic tissue^{56,57}.

Due to differences in flute and blade design, endodontic instruments vary in their debris removal efficacy and their smear layer production. Comparison of the cleaning ability of various NiTi systems is difficult, since most of the studies evaluated only one or two different rotary systems.

Post-operative cleanliness can be evaluated histologically or with SEM using longitudinal^{17,58,59} or horizontal^{60,61} sections of extracted teeth. Analyses commonly included four different parameters: inorganic debris, presence of smear layer, pulpal debris and surface profile^{17,58,59}.



■ Inorganic debris

Evaluation of remaining inorganic debris showed that LightSpeed and GT rotary were effective in cleaning all sections of the root canal^{58,62}. In contrast, with K3, Hero642, RaCe, ProTaper, FlexMaster, ProFile and Mtwo there was significantly more inorganic debris in the apical third compared with the middle and coronal third of the root canal^{13,15,17,27,28,59,63}.

Statistically significant differences in cleaning ability of the different rotary NiTi instruments have been reported^{12,13}. Root canals prepared with Mtwo had significantly less debris than RaCe and K3¹², and RaCe achieved better results than ProTaper instruments¹³; however, the differences were not always demonstrated^{17,26,27,59,60}.

Comparisons between rotary NiTi instruments and stainless steel hand instruments suggest that the manual technique with stainless steel instruments results in an equivalent cleaning ability^{17,58} or performs even better, with significantly less residual debris^{14,15,63}.

■ Smear layer, pulpal debris

Another parameter concerning cleanliness inside the root canal is the remaining smear layer and pulpal debris. Various studies showed significantly more smear layer and pulpal debris remaining in the apical third of the root canal compared with the coronal and the middle third^{17,28,58,59}.

As for the smear layer, various NiTi instruments produced similar results to the conventional manual technique using stainless steel files^{13,17,26,59}. No significant differences between different NiTi systems were reported^{12,13,17,26,59}. Remnants of pulpal debris are generally rare, and have only been observed in the apical third of the canal, revealing irregularities of the root canal wall such as grooves and depressions^{17,59}.

■ Surface profile

For the parameter 'surface profile', significant differences with respect to the localisation of irregularities inside the canal were reported^{17,59}. No grooves or other superficial irregularities were detected in the coronal or middle thirds of root canal⁵⁹. Grooves and irregularities were only present in the apical third¹⁷.

The apical third remains the critical area of the root canal. From current literature, it can be assumed that rotary NiTi instruments clean the coronal and middle third of root canal effectively and create a smooth surface profile. In the apical part of the root canal great amounts of remaining pulpal and inorganic debris could be detected^{17,59}. In addition, the profile showed a partially inhomogeneous surface and remaining smear layer after the use of different rotary NiTi instruments^{17,59}.

With regard to cleaning ability, it is interesting to note that stainless steel instruments used with the manual technique have equal or even better results than NiTi instruments^{14,15,17,58,63}. The differing results could be attributed to the use of freshly extracted or stored teeth^{17,27}, root canal preparation following decoronation or through an access cavity^{17,26,27,59}, or to varying irrigating solutions and protocols^{17,26,27,59}.

■ Shaping ability

■ Straightening

Another important aspect for successful root canal treatment is the potential straightening of curved canals during root canal preparation. The parameter 'straightening' refers to whether a root canal instrument maintains the original shape of the curved canals. Furthermore, this parameter provides information about the position of the removed material. Removal of infected dentine should be performed uniformly on the outer as well as on the inner side of the root canal's curvature in order to reduce the risk of perforation. Root canal straightening is frequently determined as the difference between the angle of the curvature assessed before and after instrumentation^{26,27,60}.

Recent studies report good maintenance of the curvature in severely curved root canals using NiTi instruments^{24,27,60}. Nevertheless, statistically significant differences in the straightening effect among rotary NiTi instruments have been demonstrated^{12,13}. In comparison with the ProTaper system, RaCe instruments caused less straightening of curved root canals¹³. The high flexibility of RaCe could be one reason for maintenance of root canal curvatures³⁵. However, it has al-



so been reported that RaCe and ProTaper maintained the curvature equally and no differences were detected; the mean degree of straightening was reported to be less than 1° for both systems²⁷.

Further studies also reported inferior results for ProTaper instruments compared with GT rotary system, Hero 642²⁴, as well as ProFile¹⁹. Hero642 and FlexMaster did not differ with respect to the straightening effect^{24,60}, probably due to a similar flexibility³⁵. A recent study reported that Mtwo instruments maintained the original canal curvature significantly better than K3 and RaCe¹².

Various studies have demonstrated a superior ability of preserving the original root curvatures by rotary NiTi instruments compared with stainless steel hand instruments^{14,15,64}. The hand instruments produced a more pronounced straightening of the curved canals. However, a recent study revealed no statistical differences between rotary NiTi instruments and stainless steel hand instruments²⁴.

■ Centring ability

The centring ability of an instrument refers to the dimension and direction of canal transportation during root canal instrumentation. Displacement of the root canal towards the furcation as well as transportation towards the outer curvature in the apical part of the root canal increases the risk of perforation.

Several investigations showed good centring abilities of NiTi instruments, with only minor deviations from the main axis of the root canal^{12,13,19,65-69}. The use of NiTi instruments decreased the prevalence and degree of transportation and straightening compared with hand instruments. Nevertheless, these effects could not be entirely eliminated. A slight widening of the apical part of root canal towards the outer side of the curvature was observed after using Hero642⁷⁰, K3^{20,28,65,69}, ProFile^{19,69,71}, RaCe²⁰, ProTaper^{19,21}, FlexMaster²² and GT rotary^{19,71}. In addition, slight centre displacement and transportation towards the furcation at the coronal part of root canal was reported after use of GT rotary system^{19,68}, ProFile¹⁹, ProTaper⁶⁵ and LightSpeed⁶⁸. Furthermore, differences between the investigated rotary NiTi systems were detected regarding their centring ability^{20,21,66,67}.

Evaluation of Mtwo rotary systems showed a perfect centring ability, with removal of material uniformly both on the outer and inner side of the curvature⁷², and better apical preparation than K3 and RaCe^{20,72}.

RaCe demonstrated superior centring ability compared with ProTaper instruments, which showed transportation towards the outer side of the curvature in the apical part of the root canal^{21,66}. Less transportation has been detected for ProTaper instruments compared with ProFile, but these differences were not statistically significant⁶⁷.

Rotary NiTi instruments have significantly better centring ability than stainless steel hand instruments^{22,28,29,70}. It can be concluded that rotary NiTi instruments preserve the original shape of the curved canals and thus reduce the risk of perforation compared with hand instruments. The straightening and centring ability vary amongst the different NiTi systems, possibly due to their flexibility (size and taper).

■ Unprepared areas

Recently, micro computed tomography (μ CT) was introduced to evaluate three-dimensional shapes of canals. This innovation allows the evaluation of geometrical changes in the prepared canals in more detail⁷³.

Different rotary NiTi systems were evaluated regarding their cleaning ability. The results indicated large untreated areas on the canal wall after using rotary NiTi systems. These areas tended to be on the convex curvature at mid-root and the concave side of the curvature more apically⁷⁴. The ProTaper system left untouched areas amounting to 43% to 49% of the root canal walls after preparation⁷⁴. Similar findings have been reported in a further study that included the NiTi systems GT rotary, LightSpeed, and ProFile⁷⁵. Approximately 35% to 40% of the root canal surface was not prepared, and no significant differences between the systems were noted⁷⁵. Furthermore, analyses of canal geometry and effects of shaping ability using FlexMaster revealed no difference compared with other NiTi systems. The untreated root canal wall areas were calculated and ranged from 37% to 47%²³. These findings highlight the need for an efficient irrigation and shaping regime to clean the root canals effectively.



■ Conclusions

The preparation of the root canal using new generation rotary NiTi files can be regarded as predictable. Nevertheless, the result of canal instrumentation may be affected by the inherent canal anatomy.

The choice of a specific rotary system for daily use requires consideration of the combined evaluation of all described parameters. Direct comparisons between various studies are difficult, due to varying experimental set-ups and investigated parameters.

To minimise the risk of instrument fracture, the use of NiTi rotary instruments requires practise before clinical use. In addition, torque-controlled motors not exceeding the recommended speed for the specific system should be used. The file should be used in an 'in-and-out' (pecking) motion with light apical pressure. Furthermore, to reduce the risk of instrument fracture, a glide path should be created prior to rotary preparation, using hand instruments.

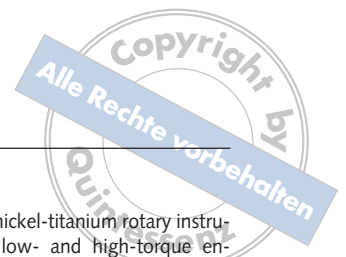
Even if manual preparation leads to an equivalent or even better cleaning ability with significantly less debris, it seems likely that straightening of the curved canals when using stainless steel files is more pronounced. In summary, NiTi instruments have sufficient cleaning ability and can preserve the root canal anatomy. Nevertheless, remaining untreated areas on the canal wall highlight the demand for more efficient irrigation. Appropriate handling of engine-driven NiTi systems, in combination with sufficient irrigation, facilitates endodontic treatment.

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