Review Article

Single-file rotary system: current concepts and their implementations

Theerapon Nuntakarat, Chanakarn Sinsareekul
Department of Operative Dentistry, Faculty of Dentistry, Chulalongkorn University

Abstract

The single-file rotary instrumentation technique was introduced as an alternative method for root canal instrumentation, offering advantages such as simplicity, reduced treatment time, operator fatigue reduction, cost-effectiveness, and minimal instrument use. With advancements in product selection and properties, the objectives of mechanical instrumentation can be effectively achieved using this technique. Several commercial types of these instruments, produced by different manufacturers, have currently become available by modifying the characteristics of the NiTi alloy and also the cross-sectional shapes, cutting edges, tapering and flute configurations. The aim of this article is to review current concepts surrounding single-file NiTi rotary systems, focusing on their shaping ability, cleaning efficacy, debris extrusion, cyclic fatigue resistance, and their effectiveness in endodontic retreatment compared to multiple-file systems. While conclusive evidence in some areas remains limited, studies indicated that single-file systems demonstrate comparable cleaning effectiveness to multiple files instrumentation.

Keywords: Single-file rotary system, Nickel Titanium instruments, Root canal preparation, Cyclic fatigue, Root canal retreatment

Correspondence: Chanakarn Sinsareekul
Department of Operative Dentistry, Faculty of Dentistry, Chulalongkorn University
Contact number: 083-275-9760
E-mail: Chanakarn.Si@chula.ac.th

Received: 20 May 2024 **Revised:** 23 July 2024 **Accepted:** 19 August 2024

Introduction

The principal objectives of endodontic instrumentation are root canal disinfection, shaping for placement of medications and facilitate root canal obturation. Mechanical instrumentation can be achieved by either using hand instruments, or engine-driven rotary instruments. With the advancement in modern technologies, nickel-titanium (NiTi) rotary instruments were developed to improve the quality of mechanical instrumentation, along with reducing clinical chair-time and fatigue generated to the clinician during the procedure. Standard of treatment currently relies on using NiTi rotary instruments for root canal cleaning and shaping. Their improvement contributes to higher favorable outcome in terms of healing, and lower the occurrence of procedural errors compared to instrumentation with stainless steel (SS) hand instruments (1, 2). Since the introduction of NiTi rotary into endodontic therapy during the mid-1990s, several improvements have been made among different generations regarding their flute and cutting angles design, metallurgy, mechanical properties, manufacturing treatment, mode of motion, and clinical performance. In addition, the development also involved with issues about number of instruments required for each preparation. As it is more simple, beneficial, and cost-effective to reduce the number or sequence of instruments while concurrently fulfilling the objectives of mechanical instrumentation. Therefore, this article reviews the current concept of single-file NiTi rotary systems, with available evidence that compared to multiple-file system in terms of shaping and cleaning ability, debris extrusion, cyclic fatigue resistance, and their effectiveness in retreatment.

Principles and origin of concepts

The introduction of a single-file rotary instrumentation technique was reported as a preliminary observation in 2008 by Dr. Ghassan Yared, with the use of only one F2 ProTaper NiTi rotary instrument (Tulsa Dentsply, Tulsa, OK, USA) in a reciprocating motion to complete canal preparation successive to canal negotiation with size 08 hand instrument. This was done in several cases regardless of canal width and apical sizes. Initially, the aim was to offer an alternative method to a standard instrumentation technique with multiple rotary files, thereby addressing the cost-effectiveness of reducing the number of instruments (3). Moreover, clinicians would require a shorter learning curve to familiarize with the instrument, leading to reduced working time to achieve the desired canal preparation shape (4). This was considered a breakthrough in instrumentation owing to the fact that F2 ProTaper instrument was originally designed for continuous rotation, not reciprocation. Even though the reciprocating motion has been clinically performed with SS instruments since the 1950s, the angles of rotation used were different. The reciprocating angle was formerly equal at 90° clockwise (CW) and counterclockwise (CCW) rotation, meanwhile Dr. Yared set the rotations to an unequal angle of four-tenth and two-tenth of a circle in CW and CCW motion, respectively. This angle of rotation was determine based on an unpublished thesis results by Thompson in 2006, which studied the rotational angle that could likely cause F2 ProTaper instrument to fracture if binds to dentin (5). Despite the successful outcome of the cases, parameters such as shaping and cleaning ability, debris extrusion, cyclic fatigue resistance, effectiveness in retreatment, and necessity to pre-flared the canal were still needed to be evaluated. Additionally, laboratory and clinical studies were lacking to provide further recommendations for using single-file system in clinical setting.

However, similar to multiple-file systems, a single-file instrument is recommended to be single use to prevent transmission of infectious disease, and decrease the chance of possible cross-contamination between patients. As previous studies found that even with thorough cleaning with ultrasonic and sterilization process, organic debris and parts of the instrumented dentinal structure can still be observed along the surface of NiTi rotary instruments (6, 7).

Development of single-file rotary systems: From past to present

Several manufacturers have launched different products into the market through the years. Currently, the systems are available in both continuous rotation and reciprocation motion. Examples of the reciprocating single-file systems are WaveOne (Dentsply Maillefer, Ballaigues, Switzerland), and Reciproc (VDW, Munich, Germany), which are the pioneers of the manufactured single-file system launched into the market since 2011 (8). Both products are initially developed based on the concept of Dr. Yared, categorized as the fourth generation of NiTi instruments as classified by Haapasalo and Chen (9), and were made with heat-treated M-wire alloy (SportsWire, Langley, OK) (10).

WaveOne rotated at unequal reciprocating angles of 150º CCW and 30º CW, completed a full 360° rotation after three rotating cycles. The product was available in three different sizes depending on the initial anatomy of the root canal used, and each was recommended to discard after single usage. Their "Small" instrument (ISO #21 tip, label in yellow) was fixed taper at 6% along its cutting part. While the taper of "Primary" (ISO #25 tip, label in red) and "Large" (#40, label in black) were fixed at 8% up to 3 mm from the cutting tip, with a progressively decreasing taper at the rest of the cutting part towards the shaft (9, 11). The instrument was uniquely designed as a non-cutting guiding tips with reverse cutting blades, rotated in a reciprocation motion, with two different triangular cross-sectional designs between the apical and coronal active parts (11, 12). Due to technology advancement, this single rotary file system had improved in its properties and developed as WaveOne Gold (Dentsply Maillefer, Ballaigues, Switzerland). The major difference between its predecessor is the size of the files, which are now available in 4 sizes, "Small" (20/07, label in yellow), "Primary" (25/07, label in red), "Medium" (35/06, label in green), and "Large" (45/05, label in white). Besides, tapering at 3 mm from the cutting tip is fixed, while the rest of the active part has progressive decrease in taper design (13). Moreover, WaveOne Gold was manufactured by a special thermo-mechanical process of repetitive heating and cooling NiTi instruments in several cycles, alongside with lower amount of nickel content compared to conventional NiTi instruments. These file elicit better shape memory effect, which is they do not rebound to their original shape after unloading (14). Thereby producing lower stress values, providing more flexibility profile to the instruments, and withstand to cyclic fatigue when compared to the original WaveOne files (15-17).

Reciproc instruments were manufactured with an S-shaped cross-sectional design, with shorter shaft of 11 mm when compared to other available brands. They were available in three different sizes with regressive taper, R25 (ISO #25 tip, 0.08 taper), R40 (ISO #40 tip, 0.06 taper), and R50 (ISO #50 tip, 0.05 taper) (9). Meanwhile their successor, the Reciproc Blue (VDW, Munich, Germany), were developed with additional heat treatment of the surface similar to WaveOne Gold. It is also shown to be that the instruments are more flexible, exhibit lower bending resistance, reducing the risk of instrument fracture when compared to their original Reciproc instrument (18). Another file system that was manufactured with similar thermo-mechanical machining process is the V-Taper 2H (SS White, Lakewood, NJ, USA). Which is another controlled memory (CM) wire-based file system that is also claimed to be a single-file with variable pitch and variable taper design (19, 20).

Apart from the aforementioned file systems, another example of the file system that is categorized as the fourth generation NiTi instruments is the Self-Adjusting File (ReDent-Nova, Ra'anana, Israel). It is a single-file system with totally different concept of instrument design and mode of instrumentation. It has a hollow design with network of thin NiTi lattice and mild abrasive surface to remove dentinal structures. Upon insertion, they can be compress into the root canal, and can adapts to the canal configurations in three dimensions during instrumentation (9). In adjunct to the in and out vibrating motion, the file can provide simultaneous irrigation during instrumentation. As a special irrigation device can be connected to the tube which acts as an irrigation hub on the file (21). However, this system requires canal negotiation or pre-flared with at least size 20 K-file prior usage of the instrument (22).

XP-endo Shaper (FKG Dentaire, La Chaux-de-Fonds, Switzerland) is a file system that was launched in 2015 and claimed by the manufacturer to be super elastic. It is manufactured from MaxWire alloy that consists of two phases: Martensitic (M) phase with relatively straight and initial tapering of 0.01 at room temperature, and Austenitic (A) phase with curved shape and tapering of 0.04 when exposed to body temperature. The curved shape of the instrument mimics the shape of a snake, and its final instrumentation size equals to 30/04 when use as a single-file (23-25).

In 2016, HyFlex EDM (Coltene/Whaledent, Altstätten, Switzerland) was launched and introduced as the first instrument manufactured by electrodischarge machining (EDM) process (26). Which is a procedure that uses electric current to generate high frequency sparks that melts the wire by erosion process without contacting the instruments (26). Their main shaping instrument is the variable tapering size 25 file, with additional finishing files available in size 40/.04, 50/.03, and 60/.02. The instrument is presented with different cross-sectional design along its length. With quadrangular shape at the tip, transforming into rectangular in the middle, before becoming triangular toward the shaft (14).

One of the first available continuous rotation single-file system is the One Shape (Micro Mega, Besancon, France). It was designed to use in a full clockwise rotation, with only one available instrument of an ISO size 25, and 0.06 constant tapering. Its cross-sectional shape is different throughout various levels of the instrument, with three symmetrical non-cutting edges at the tip.

Then towards the middle part, its cross-sectional design slightly changes into asymmetrical three cutting edges, to two cutting edges, and becoming two cutting edges with S-shaped cross-section near the shank (27, 28). The asymmetrical design aim to reduce binding of instrument due to the nature of continuous movement (29). Other examples from the same manufacturer is the One Curve system (Micro Mega, Besancon, France), which was launched in 2017. One Curve also rotate in continuous movement and is manufactured from heat-treated NiTi, known as the C wire (30). It is available with four tip sizes: 25/04, 25/06, 35/04, and 45/04. Their main features are the shape memory effect, and pre-bending ability which can provide easier access into the root canals (31).

Another continuous rotation single-rotary file system launched in 2019 is TruNatomy (Dentsply Sirona, Ballaigues, Switzerland), which is manufactured from a relatively smaller wire blank of 0.8 mm diameter, when compared to other rotary systems at 1.1 mm diameter. This instrument system is claimed to provide better access and easier placement into the root canal, as its handle length has been reduced to 9.5 mm. TruNatomy preparation instruments are also available in three tip sizes, the Prime instrument (ISO #26 tip, label in red, with an overall decreasing taper at average of 0.04), the Medium instrument (ISO #36 tip, label in green, with an overall decreasing taper at average of 0.03), and the Small instrument (ISO #20 tip, label in yellow, with taper of 0.04) which is recommend for extremely curved canals or canals that were difficult to achieve glide path (32).

In recent years, other several single-file systems were introduced into the market. Each were presented with different distinctive features, designs, and performance. One is the E-Flex Edge file system (Eighteeth, Changzhou, China), which is available in three tip sizes: 20, 25, and 35, each with either 04 or 06 tapering. Files of this system are also available with different heat treatments, Silver, Gold, and Blue. Their main feature is the flat-sided design, which is claimed by the manufacturer that they can be easily bypass or retrieve when fracture inside the canal owing to more provided space between the instrument and the canal. Other systems from the same manufacturer are the E-flex One, which is also manufactured with blue heat treatment, and the E-Flex Rec, which rotates in reciprocation motion. Both systems are available with the same tip size and taper similar to the E-Flex Edge system.

Another available system is the M3 files (UDG, Changzhou, China), that are available with different series of products in which designs and metallurgy resembles some of the aforementioned systems, for example, M3 W-One Gold, M3-RG, M3-RB, M3-EDM, and M3-L Platinum. Another available reciprocating motion single-file system is the EdgeOne Fire system (EdgeEndo, Albuquerque, NM, USA), which resembles WaveOne Gold in their cross-sectional design, and handpiece settings. This system is manufactured from a heat process called FireWire™, which is claimed to provide restoring force and high flexibility to the instruments (33).

With the advancement in technology, metallurgy, and manufacturing process, development of rotary files continues with the aim to enhance their physical and mechanical properties. Some changes can be made which require clinicians to become familiarize with or keeping up to date to provide the best clinical performance.

Establishing glide path: Is it necessary for the single file rotary system?

A preliminary report published by Dr. Yared has provided key insights into his proposed technique. Outcomes were compared between the single-file F2 ProTaper preparation and full-sequence ProTaper preparation using microcomputed tomography to evaluate anatomical parameters and the time required for complete instrumentation. Results showed that apart from the significantly reduced instrumentation time with single F2 ProTaper instrument, other parameters were not statistically different (34). These findings align with another report that tested different file systems (35). This raises the question of whether a glide path is still necessary when using a single-file system.

The endodontic glide path is defined as a smooth pathway from the canal orifice to the physiological terminus of the root canal that guide shaping instruments to follow the path (36). Establishing a glide path is essential before introducing NiTi instruments. This step facilitates the advancement of larger instruments, reducing the risk of instrument fracture due to binding with dentin and torsional fracture, which eventually improved safety and predictability of root canal instrumentation with NiTi instruments (8, 37). The concept of the single-file system suggested that it may require only minimal or no prerequisite of a glide path (38), which was also claimed by manufacturers. According to a study by De-Deus and colleagues (39), working length in straight canals and canals with moderate curvature can be achieved with only Reciproc R25 instrument, even without a pre-established glide path. Moreover, 67% of the canals that were non-negotiable with a size #10 K-file were able to reach the desired length with only single R25 instrument. The favourable outcomes may be accredited by the angles used in reciprocation, flexibility and cutting ability of the instruments.

However, concerns may arise regarding preparation in severely curved canals. While many studies suggest that full working length can be achieved without creating a glide path in most non-complex root canals, the use of glide path files (particularly in canals with severe curvature) prior to single-file instrumentation results in more centered preparation, reduced canal transportation, and tends to improve the shaping ability of the single-file system (40, 41). Additionally, even in the novel publication by Dr. Yared who proposed this instrumentation concept, he also mentioned that one limitation of the technique is their implementation in a sharp, non-gradual canal curvature. A patent minimal glide path should be established to ensure complete advancement of the instrument beyond the curve, and to achieve adequate preparation in severely curved canals or canals with double curvature (3).

Shaping ability, and occurrence of dentinal defects

It is essential for NiTi instruments to be used with optimum cutting efficiency, maintaining the original root canal anatomy, and minimizing the formation of dentinal defects during instrumentation. Dentinal defects such as deviations, ledges, zips, canal transportation, and perforations may occur during canal enlargement, especially in narrow and curved canals (42). These defects can lead to inadequate or ineffective cleaning and shaping of the root canal (43).

Several parameters are used to analyze the shaping ability and occurrence of dentinal defects, including evaluation of unprepared areas of the root canal, root canal volume, canal transportation, centering ability, and the straightening effect of the file. Assessment can be conducted using radiographs (44), or microcomputed tomography (micro-CT) (19, 45-53). The most widely used evaluation method is micro-CT, as it preserves sample integrity, facilitates both quantitative and qualitative assessment, and enables image reconstruction in either two or three dimensions (43).

Reciproc and WaveOne have been extensively studied in many research investigations (19, 44-50). Several studies have found no significant differences between these systems and several tested multiple-file systems, such as ProTaper Universal, ProTaper Next, and MTwo, in terms of canal transportation, centering ability, and changes in canal volume However, conflicting results have been reported in some studies, suggesting that both Reciproc and WaveOne may induce greater canal transportation compared to systems like HyFlex CM or TF Adaptive (48, 49). The discrepancies in these studies may contribute from using larger taper instruments to the working length without pre-enlarging the canals. The flutes of larger instrument can bind with dentin, creating greater engagement and torque applied, which may contribute to greater canal transportation. In addition, tapering of instruments may affect canal transportation. As a less taper instruments may elicit good flexibility, which may contribute to lesser canal transportation and better centering ability (19).

Another aspect tested is the time required for complete canal instrumentation, with all tested single-file systems demonstrating significantly faster preparation times compared to full sequence instrumentation (35, 54, 55). These findings are consistent with observations previously reported by Dr. Yared (3).

Table 1 Summary of shaping ability, and occurrence of dentinal defects of different single-file systems compared to multiple-file systems.

Authors	Sample	Single-file Instruments	Movement	Methods	Evaluated parameters	Conclusions
Kim et al. 2013 (45)	MB and DB canals of maxillary molars with 20-45 degrees curvature	WaveOne Primary	Reciprocation	micro-CT	Canal volume change	No differences compared to ProTaper Universal (P > 0.05).
					Surface area	
					Centering ability	
					Canal transportation	
Hwang et al. 2014 (46)	MB and DB canals of maxillary molars	Reciproc R25	Reciprocation	micro-CT	Canal volume change	No differences compared to MTwo (P > 0.05).
					Canal transportation	Reciproc R25 showed significantly lower coronal and apical transportation compared to Mtwo (P < 0.05).

Table 1 Summary of shaping ability, and occurrence of dentinal defects of different single-file systems compared to multiple-file systems. (continued)

Authors	Sample	Single-file Instruments	Movement	Methods	Evaluated parameters	Conclusions
McRay et al. 2014 (47)	Mesial roots of mandibular molars	WaveOne Primary	Reciprocation	micro-CT	Centering ability	No differences compared to ProTaper Universal (P > 0.05).
					Canal transportation	
Marceliano-Alves et al. 2015 (48)	Mesial roots of mandibular molars	Reciproc R25	Reciprocation	micro-CT	Changes in canal area and perimeter	Reciproc showed significantly greater apical enlargement of the root canal (P < 0.05).
					Canal volume change	No differences between systems (P > 0.05).
		WaveOne Primary	Reciprocation		Canal transportation	Both Reciproc and WaveOne showed significantly greater canal transportation compared to HyFlex CM (P < 0.05).
Gergi et al. 2015 (49)	Mesial roots of mandibular molars with severe curvature	Reciproc R25	Reciprocation	micro-CT	Canal volume change	Reciproc showed significantly greater overall and apical dentin removal (P < 0.05).
					Amount of unprepared surface	No differences between systems (P > 0.05).
		WaveOne Primary	Reciprocation		Canal transportation	Both Reciproc and WaveOne showed significantly higher canal transportation compared to TF Adaptive (P < 0.0001).
					Centering ability	Both Reciproc and WaveOne showed significantly lower centering ability compared to TF Adaptive (P < 0.0001).
Venino et al. 2017 (51)	All teeth	HyFlex EDM	Continuous	micro-CT	Canal transportation	No differences compared to ProTaper Next (P > 0.05).
					Centering ability	
					Canal volume change	
Lacerda et al. 2017 (52)	Distal roots of mandibular molars	XP-endo Shaper size 30	Continuous	micro-CT	Amount of unprepared surface	No differences compared to TRUShape (P > 0.05).
		Self-Adjusting File	Vibration			

Apical Debris Extrusion

During root canal instrumentation, dentin chips, pulp tissues, or even microorganisms may be push towards the apex, potentially leading to post-operative pain and complications. It has been observed that all instrumentation techniques resulted in varying degrees of debris extrusion, even when instrumentation is short of the apical foramen (56). Methods for measuring apical debris extrusion can vary among studies, with a commonly used technique being the method described by Myers and Montgomery in 1991. In this method, the extruded contents are collected in a container, moisture is evaporated, and only the extruded debris is weighed directly (57).

Table 2 Summary of apical debris extrusion of different single-file systems compared to multiple-file systems.

Authors	Sample	Single-file Instruments	Movement	Methods	Evaluated parameters	Conclusions
Bürklein & Schäfer, 2012 (56)	Mandibular central incisors	Reciproc R40 WaveOne Large	Reciprocation Reciprocation	Myers and Montgomery method	Apically extruded debris	Both Reciproc and WaveOne showed significantly greater amount of apically extruded debris compared to Mtwo and ProTaper ($P < 0.05$).
Bürklein et al. 2014 (58)	Mandibular central incisors	Reciproc R25	Reciprocation	Myers and Montgomery method	Apically extruded debris	Reciproc showed significantly greater amount of apically extruded debris compared to MTwo ($P < 0.05$).
		OneShape size 25	Continuous			OneShape showed no difference in the amount of apically extruded debris compared to Mtwo ($P > 0.05$).
Ozsu et al. 2014 (59)	Mandibular premolars	WaveOne Large Self-Adjusting File	Reciprocation Vibration	Myers and Montgomery method	Apically extruded debris	Self-Adjusting file showed least debris extrusion ($P < 0.05$), followed by ProTaper Next and WaveOne with no significant difference ($P > 0.05$), then ProTaper Universal with the most extruded debris ($P < 0.05$).
Silva et al. 2016 (60)	Mandibular premolars	WaveOne Large Reciproc R40	Reciprocation Reciprocation	Myers and Montgomery method	Apically extruded debris	No significant differences in the amount of apically extruded debris between WaveOne, Reciproc, and ProTaper Next ($P > 0.05$), while ProTaper Universal was associated with significantly greater amount of apically extruded debris ($P < 0.05$).
da Silva et al. 2021 (61)	Mandibular premolars	Reciproc Blue R40	Reciprocation	micro-CT	Apically extruded debris	Reciproc Blue showed no significant differences in apically extruded debris compared to ProTaper Universal, and TRUShape ($P > 0.05$).

Results regarding apical debris extrusion were varying among studies. Some study reported that debris extrusion is more significant when using single-file systems compared to full instrumentation sequences (56). This difference may arise because of the removal of certain amount of dentin in the coronal part with the initial files of multiple sequence file systems. This initial dentin reduction can reduce apical force pressure and subsequently decrease the extrusion of debris beyond the apices (62). However, the designs of Self-Adjusting files may contribute to contradictory result. In which the lattice network allows continuous irrigation while simultaneously removing dentinal debris out of the canal, which reduced the amount of apically extruded debris (59). Moreover, other studies have reported no significant differences in the amount of debris extrusion between single and multiple-file systems (61). Additionally, some studies have reported varied outcomes, possibly due to variations in the files tested across studies (58, 60).

It has been suggested that movement kinematics of the tested instruments may contributed to difference in amount of debris extrusion. Instruments with continuous rotation may deliver cutting debris or dentin chips coronally as their movement acts like a screw conveyor, which results in lower amount of debris extrusion (56).

Cleaning ability

The primary cause of apical periodontitis is the presence of bacteria or microorganisms in the root canal system. Thus, the main goals of endodontic treatment are to eliminate these microorganisms and prevent their re-colonization.

There are concerns regarding the efficacy of single-file instrumentation in adequately disinfecting the root canal, as the cleanliness of the canal may be compromised when fewer instruments are used. To assess the cleaning ability of a file system, bacterial elimination is a critical parameter. Results are often assessed using quantitative real-time PCR analysis of bacterial species, where DNA extraction from samples taken before and after instrumentation is compared (63, 64). Antibacterial effectiveness can also be evaluated by counting colony-forming units in bacterial cultures (65-68), quantifying endotoxin concentration (66), or examining the topography using scanning electron microscopy (SEM) (19, 67).

According to table 3, no significant differences in bacterial reduction between single-file and multiple-instrumentation systems were reported among studies (63, 65, 66). Moreover, most studies have consistently found that while single-file systems can reduce cultivated bacteria, they may not achieve complete sterilization of the canal (63, 64, 66-68). However, the aforementioned studies were conducted in laboratory settings, either *in vitro* or *ex vivo*, and the result may not directly apply to clinical conditions. Clinical studies should be further conducted to evaluate bacterial reduction profile and microbiome conditions following instrumentation with different systems.

Table 3 Summary of cleaning ability of different single-file systems compared to multiple-file systems.

Authors	Sample	Single-file Instruments	Movement	Methods	Evaluated parameters	Conclusions
Machado et al. 2013 (65)	DB roots of maxillary molars	WaveOne Primary	Reciprocation	Bacterial count (CFU/mL)	*E.faecalis* bacterial load	When compared to ProTaper and MTwo, all tested groups were effective in reducing bacterial counts with no significant difference between systems (P > 0.05), but all still have detectable bacteria after instrumentation.
		Reciproc R25	Reciprocation			
Martinho et al. 2014 (66)	Single root teeth with single canal	WaveOne Primary	Reciprocation	Chromogenic limulus amebocyte lysate assay	Endotoxin quantification	When compared to ProTaper and MTwo, all tested groups were effective in reducing bacterial counts with no significant difference between systems (P > 0.05), but all still have detectable bacteria after instrumentation.
		Reciproc R40	Reciprocation	Bacterial count (CFU/mL)	Cultivable bacteria	
Neves et al. 2016 (63)	Single root teeth with single canal	Reciproc R40 or R50	Reciprocation	DNA extraction and Quantitative Real-time PCR	Level of total bacteria and Streptococci	Effective in reducing bacterial counts with no significant difference compared to BioRace (P > 0.05), but still have detectable bacteria after instrumentation.

Cyclic fatigue resistance

Despite the advantages of NiTi rotary systems, their major concern is the separation of instrument, which can results from either torsional failure, cyclic fatigue, or a combination of both (69). According to the Glossary of Endodontic Terms (10^{th} Edition), torsional failure occurs when certain parts of the instrument bind to the root canal wall while the handpiece continues to rotate, surpassing the elastic limit of the files and leading to fracture. While cyclic fatigue refers to failure of an instrument due to repetitive stress caused by work hardening and metal fatigue, causing microcracks initiation and eventually propagates until fracture. Several advancements have been made to reduce instrument breakage, focusing on improvements in cross-sectional design, cutting motion, metallurgy, heat treatment, and machining processes of the instruments. These developments directly affect the physical properties of the files, enhancing their resistance to cyclic fatigue.

Cyclic fatigue testing of NiTi rotary files is the assessment of operated instruments until fracture is visually detected, then evaluation can be made in relation to time to fracture, so that number of cycles to fracture (NCF) can be recorded. NCF can be evaluated under various conditions, such as room temperature or body temperature, which can induce austenitic transformation and reducing cyclic fatigue resistance when tested at body temperature (31, 70). Which means the file are sensitive to temperature changes, and elicit different properties according to each specific heat capacities due to different phases of the material (71). It has been suggested that time to fracture is a more realistic measure, especially for single-file systems, as NCF may not accurately predict clinical lifespan (72). However, results can vary among studies due to the lack of consensus on testing standards and models used for cyclic fatigue testing of NiTi instruments.

Table 4 Summary of cyclic fatigue resistance of different single-file systems compared to multiple-file systems.

Authors	Sample	Single-file Instruments	Movement	Methods	Evaluated parameters	Conclusions
Pedulla et al. 2013 (73)	Artificial root canal with 60 degrees curvature	Reciproc R25	Reciprocation	Time to fracture recorded.	Number of cycles to fracture (NCF)	When compared to MTwo and Twisted File size 25 which rotated in continuous motion, both Reciproc and WaveOne showed significantly higher cyclic fatigue resistance (P < 0.05).
		WaveOne Primary	Reciprocation			
Dagna et al. 2014 (74)	Stainless steel canals with 45-60 degrees curvature, and 5-8 mm radius	OneShape size 25	Continuous	Time to fracture recorded.	Number of cycles to fracture (NCF)	Reciproc showed highest cyclic fatigue resistance (P < 0.05), followed by WaveOne and OneShape, then ProTaper F2.
		Reciproc R25	Reciprocation			
		WaveOne Primary	Reciprocation			
da Frota et al. 2014 (75)	Artificial root canal with 45 degrees curvature, and 5 mm radius	Reciproc R25	Reciprocation	Time to fracture recorded.	Number of cycles to fracture (NCF)	When compared to ProTaper F2 and MTwo size 25 which rotated in continuous motion, both Reciproc and WaveOne showed significantly higher cyclic fatigue resistance (P < 0.05).
		WaveOne Primary	Reciprocation			
Kiefner et al. 2014 (76)	Artificial root canal with 60 degrees curvature	Reciproc R25 and R40	Tested in both reciprocation and continuous.	Time to fracture and push-pull cycles recorded.	Number of cycles to fracture (NCF)	Reciprocation can increase cyclic fatigue resistance of NiTi instruments (P < 0.05). Same results and conclusion applied when tested with MTwo.
Al-Obaida et al. 2022 (77)	Stainless steel artificial root canal with 40 degrees curvature and 5 mm radius	WaveOne Primary	Reciprocation	Time to fracture recorded.	Number of cycles to fracture (NCF)	WaveOne showed significantly higher cyclic fatigue resistance compared to Reciproc and ProTaper F2 (P < 0.05).
		Reciproc R25	Reciprocation			

In evaluating cyclic fatigue resistance, the kinematics of movement are more critical than the number of file sequences used. Rather than comparing single-file and multiple-file systems, studies have focused on different modes of movement. Results coincide among several studies indicating that systems using reciprocating motion tend to show longer time to fracture compared to those using continuous rotation (71, 73-78). This may be attributed to reciprocating motion requiring more time to complete the same amount of rotational cycles as continuous rotation, or due to lower operational rpm settings in reciprocating files. The result can be explained the concept of reciprocation motion that was originally developed to prevent flexural cyclic fatigue of instruments when compared to continuous rotation. However, apart from movement kinematics, other factors such as metallurgy, design, and heat treatment applied to the files can also influence the cyclic fatigue resistance properties of the instruments.

Efficiency in endodontic retreatment

In endodontic retreatment procedures, it is essential to completely remove all previous root filling materials to achieve full working length for subsequent cleaning, shaping, and obturating procedures. Several NiTi rotary file products designed specifically for retreatment purposes are available on the market. Their mechanics are rotating motion which facilitates cutting through the obturating material. These files were designed as an end-cutting tips, which enhance penetration into the gutta-percha mass. The resistance generated by these files can soften the gutta-percha, aiding in its removal.

Non-retreated rotary file systems can also be used to remove gutta percha, but require higher speeds compared to normal mechanical preparations. The file should be smaller in diameter and less tapered than the canal to prevent binding. The recommended technique is the plunge-and-withdrawl, combined with supplementary use of irrigants. The recommended motor setting should be 350-1,500 rpm, to generate sufficient resistance which can soften the gutta percha and reduce the chance of instrument fracture. However, using a high speed cutting action in curved canals can cause deviation and canal transportation (79).

According to Table 5, comparing the efficiency of single-file and multiple-file systems in endodontic retreatment is inconclusive. Retreatment efficiency is assessed using several parameters, such as the amount of remaining gutta percha (which is mostly perform with CBCT or micro-CT scans), the amount of debris generated, the time required to re-establish the working length, or the complete elimination of clinically visible gutta percha.

Table 5 Summary of endodontic retreatment efficiency of different single-file systems compared to multiple-file systems.

Authors	Sample	Single-file Instruments	Movement	Methods	Evaluated parameters	Conclusions
Rios et al. 2014 (80)	Maxillary incisors	Reciproc R25	Reciprocation	Splitting, photographed under dental operating microscope, and analyzed with Image Tool software	Remaining filling material	No differences in the amount of remaining filling material between both Reciproc and WaveOne compared to ProTaper Universal Retreatment (P > 0.05).
		WaveOne Primary	Reciprocation			
Nevares et al. 2016 (81)	Mesial roots of Mandibular molars	Reciproc R25	Reciprocation	(not mentioned)	Time to regain working length	No differences in time regaining worling length, remaining filling material, and apical transportation between Reciproc compared to ProTaper Next (P > 0.05).
				micro-CT	Remaining filling material	
					Apical transportation	
Ozyurek and Demiryurek, 2016 (82)	Maxillary central incisors	Reciproc R25	Reciprocation	Splitting and SEM analysis	Remaining filling material	Reciproc showed no significant difference to TF Adaptive (P > 0.05), but remaining filling in both Reciproc and TF Adaptive were significantly greater compared to ProTaper Next, and ProTaper Universal Retreatment (P < 0.05).
				Digital chronometer	Time to regain working length	Reciproc showed no significant difference to TF Adaptive and ProTaper Next (P > 0.05). While ProTaper Universal Retreatment showed the shortest retreatment time (P < 0.05).
Jorgensen et al. 2017 (83)	Mesial roots of Mandibular molars	WaveOne Primary	Reciprocation	(not mentioned)	Time to regain working length	Significantly greater time to reach working length compared to ProTaper Universal retreatment files (P < 0.05).

Table 5 Summary of endodontic retreatment efficiency of different single-file systems compared to multiple-file systems. (continued)

Authors	Sample	Single-file Instruments	Movement	Methods	Evaluated parameters	Conclusions
Yılmaz and Ozyurek, 2017 (62)	Maxillary central incisors	Reciproc R25 (for filling removal), and R50 (for shaping)	Reciprocation	Myers and Montgomery method	Apically extruded debris	Significantly greater amount of apically extruded debris than ProTaper Next ($P < 0.05$).
				Digital chronometer	Gutta percha removal time	No significant differences compared to ProTaper Next, and TF Adaptive in gutta percha removal time ($P > 0.05$).
Delai et al. 2019 (84)	MB canals of maxillary molars	WaveOne Gold Primary (for filling removal), and Medium (for shaping)	Reciprocation	micro-CT	Remaining filling material	No significant differences compared to ProTaper, and RaCe ($P > 0.05$). None of the systems can completely remove filling materials.
				micro-CT	Apical transportation	No significant differences compared to ProTaper, and RaCe ($P > 0.05$).
				Digital timer	Working time	When compared to ProTaper and RaCe, WaveOne Gold was significantly faster in shaping ($P < 0.05$), but no significant differences among groups in filling removal ($P > 0.05$).
Abdelnaby et al. 2023 (85)	Mesial roots of Mandibular molars with 10-20 degrees curvature	Reciproc Blue R25	Reciprocation	Myers and Montgomery method	Apically extruded debris	No significant differences compared to ProTaper Universal Retreatment combined with ProTaper Next ($P > 0.05$).
		HyFlex EDM size 25	Continuous	CBCT scans	Remaining filling material	
Tantiwanichpun and Kulvitit, 2023 (86)	Mesial roots of Mandibular molars with 20-40 degrees curvature	Reciproc Blue R25	Reciprocation	micro-CT	Percentage of root filling removal	No significant difference compared to VDW Rotate retreatment files and ProTaper Next ($P > 0.05$).
					Canal deformities	Not observed in the specimens in all tested instrument systems.
				Digital clock	Working time	Significantly longer time for reaching working length and filling removal in the Reciproc Blue group compared to VDW Rotate ($P < 0.05$).

Table 5 Summary of endodontic retreatment efficiency of different single-file systems compared to multiple-file systems. (continued)

Authors	Sample	Single-file Instruments	Movement	Methods	Evaluated parameters	Conclusions
Ciftcioglu et al. 2023 (87)	Single root mandibular premolars	Reciproc R25	Reciprocation	Digital chronometer	Time to regain working length	Reciproc Blue showed the longest time, followed by ProTaper Universal Retreatment, then XP-endo Shaper. Significant differences were observed among groups ($P < 0.05$).
		XP-endo Shaper	Continuous	Myers and Montgomery method	Apically extruded debris	XP-endo Shaper showed least apical extruded debris, followed by Reciproc Blue and ProTaper Universal Retreatment, with only significant difference between XP-endo shaper and ProTaper Universal Retreatment ($P < 0.05$).

While the single-file system is advantageous for endodontic instrumentation due to its simplicity and reduced treatment time, the same may not hold true for endodontic retreatment. According to previous studies, the treatment time required for gutta percha removal or re-establishing the working length can take longer with single-file systems (83, 86, 87). However, some studies reported that there were no differences between single and multiple-file systems regarding time required for gutta percha removal or re-establishing the working length (62, 81, 82, 84). Meanwhile, the volume of remaining gutta percha were not statistically significant difference between the single-file system and full sequence system, or retreatment files (80, 81, 84-86). Results can vary across studies due to differences in samples, retreatment protocols, assessment tools, and evaluation criteria. The effectiveness of gutta percha removal during retreatment may differ between instruments, influenced by their cutting efficiency, cross-sectional design, cutting angle, metallurgy, and kinematics (88). Some studies suggest that instruments with a slender design, narrow taper, and booster tip are more efficient for gutta percha removal. In contrast, files with a large taper may not provide adequate space for cutting debris displacement, potentially leaving more remaining gutta-percha and increasing instrumentation time (89). Despite the difference, one issue that can be concluded is that none of the tested file systems were subjected to completely remove the gutta percha from the entire root canal (84, 86).

Conclusions

The use of single-file rotary systems achieves a comparable effect in terms of cleaning efficiency to multiple instrumentation techniques, while also reducing treatment time. However, higher levels of evidence are required to evaluate their shaping ability, debris extrusion, and efficiency in endodontic retreatment. One limitation of the technique is the necessity of establishing a glide path before implementation in curved canals. Nonetheless, clinicians are encouraged to select the most suitable instrument for each case and to experiment with different systems to determine the best option based on their own judgment.

References

1. Schäfer E. Root canal instruments for manual use: a review. Endod Dent Traumatol. 1997;13(2):51-64.
2. Bürklein S, Arias A. Effectiveness of root canal instrumentation for the treatment of apical periodontitis: A systematic review and meta-analysis. Int Endod J. 2023;56 Suppl 3:395-421.
3. Yared G. Canal preparation using only one Ni-Ti rotary instrument: preliminary observations. Int Endod J. 2008;41(4):339-44.
4. Yared G, Ramli G. Single file reciprocation: A literature review. 2013;7(3):171-8.
5. Thompson N. Development of a Novel Canal Preparation Technique Using the Torsional Fatigue Profile of the ProTaper F2 Rotary Instrument. Toronto, Canda: University of Toronto; 2006.
6. Alapati SB, Brantley WA, Svec TA, Powers JM, Nusstein JM, Daehn GS. Proposed role of embedded dentin chips for the clinical failure of nickel-titanium rotary instruments. J Endod. 2004;30(5):339-41.
7. Sonntag D, Peters OA. Effect of prion decontamination protocols on nickel-titanium rotary surfaces. J Endod. 2007;33(4):442-6.
8. Liang Y, Yue L. Evolution and development: engine-driven endodontic rotary nickel-titanium instruments. Int J Oral Sci. 2022;14(1):12.
9. Haapasalo M, Shen Y. Evolution of nickel-titanium instruments: From past to future. Endodontic Topics. 2013;29.
10. Johnson E, Lloyd A, Kuttler S, Namerow K. Comparison between a novel nickel-titanium alloy and 508 nitinol on the cyclic fatigue life of ProFile 25/.04 rotary instruments. J Endod. 2008;34(11):1406-9.
11. Berutti E, Chiandussi G, Paolino DS, Scotti N, Cantatore G, Castellucci A, et al. Canal shaping with WaveOne Primary reciprocating files and ProTaper system: a comparative study. J Endod. 2012;38(4):505-9.
12. Webber J MP, Pertot W, Kuttler S, Ruddle C, West J. The WaveOne single-file reciprocating system. Roots. 2011;1:28–33.
13. Ruddle CJ. Single-File Shaping Technique: Achieving a Gold Medal Result. Dent Today. 2016;35(1):98, 100, 2-3.
14. Tabassum S, Zafar K, Umer F. Nickel-Titanium Rotary File Systems: What's New? Eur Endod J. 2019;4(3):111-7.
15. Adıgüzel M, Capar ID. Comparison of Cyclic Fatigue Resistance of WaveOne and WaveOne Gold Small, Primary, and Large Instruments. J Endod. 2017;43(4):623-7.
16. AlRahabi AMK, Atta RM. Surface nanoscale profile of WaveOne, WaveOne Gold, Reciproc, and Reciproc blue, before and after root canal preparation. Odontology. 2019;107(4):500-6.

17. Prados-Privado M, Rojo R, Ivorra C, Prados-Frutos JC. Finite element analysis comparing WaveOne, WaveOne Gold, Reciproc and Reciproc Blue responses with bending and torsion tests. J Mech Behav Biomed Mater. 2019;90:165-72.
18. De-Deus G, Silva EJ, Vieira VT, Belladonna FG, Elias CN, Plotino G, et al. Blue Thermomechanical Treatment Optimizes Fatigue Resistance and Flexibility of the Reciproc Files. J Endod. 2017;43(3):462-6.
19. Liu Y, Chen M, Tang W, Liu C, Du M. Comparison of five single-file systems in the preparation of severely curved root canals: an ex vivo study. BMC Oral Health. 2022;22(1):649.
20. Radwański M, Łęski M, Puszkarz AK, Krucińska I. Shaping Ability of ProTaper Next, Hyflex CM, and V-Taper 2H Nickel-Titanium Files in Mandibular Molars: A Micro-computed Tomographic Study. Iran Endod J. 2021;16(2):103-8.
21. Metzger Z, Teperovich E, Zary R, Cohen R, Hof R. The self-adjusting file (SAF). Part 1: respecting the root canal anatomy--a new concept of endodontic files and its implementation. J Endod. 2010;36(4):679-90.
22. Hof R, Perevalov V, Eltanani M, Zary R, Metzger Z. The self-adjusting file (SAF). Part 2: mechanical analysis. J Endod. 2010;36(4):691-6.
23. Bayram HM, Bayram E, Ocak M, Uygun AD, Celik HH. Effect of ProTaper Gold, Self-Adjusting File, and XP-endo Shaper Instruments on Dentinal Microcrack Formation: A Micro-computed Tomographic Study. J Endod. 2017;43(7):1166-9.
24. Shaheen NA, Elhelbawy NGE. Shaping Ability and Buckling Resistance of TruNatomy, WaveOne gold, and XP-Endo Shaper Single-File Systems. Contemp Clin Dent. 2022;13(3):261-6.
25. Azim AA, Piasecki L, da Silva Neto UX, Cruz ATG, Azim KA. XP Shaper, A Novel Adaptive Core Rotary Instrument: Micro-computed Tomographic Analysis of Its Shaping Abilities. J Endod. 2017;43(9):1532-8.
26. Iacono F, Pirani C, Generali L, Bolelli G, Sassatelli P, Lusvarghi L, et al. Structural analysis of HyFlex EDM instruments. Int Endod J. 2017;50(3):303-13.
27. Dagna A. Nickel-Titanium Single-file System in Endodontics. J Contemp Dent Pract. 2015;16(10):834-9.
28. Gernhardt C. One Shape - a single file NiTi system for root canal instrumentation used in continuous rotation. ENDO Endodontic Practice Today. 2013;7:211-6.
29. Bürklein S, Hiller C, Huda M, Schäfer E. Shaping ability and cleaning effectiveness of Mtwo versus coated and uncoated EasyShape instruments in severely curved root canals of extracted teeth. Int Endod J. 2011;44(5):447-57.
30. Kuzekanani M. Nickel-Titanium Rotary Instruments: Development of the Single-File Systems. J Int Soc Prev Community Dent. 2018;8(5):386-90.
31. Topçuoğlu HS, Topçuoğlu G, Kafdağ Ö, Balkaya H. Effect of two different temperatures on resistance to cyclic fatigue of one Curve, EdgeFile, HyFlex CM and ProTaper next files. Aust Endod J. 2020;46(1):68-72.
32. Vorster M. Minimally invasive endodontics using a new single-file rotary system. 2019.
33. Gambarini G, Galli M, Di Nardo D, Seracchiani M, Donfrancesco O, Testarelli L. Differences in cyclic fatigue lifespan between two different heat treated NiTi endodontic rotary instruments: WaveOne Gold vs EdgeOne Fire. J Clin Exp Dent. 2019;11(7):e609-e13.

34. Paqué F, Zehnder M, De-Deus G. Microtomography-based comparison of reciprocating single-file F2 ProTaper technique versus rotary full sequence. J Endod. 2011; 37(10):1394-7.
35. Zhao D, Shen Y, Peng B, Haapasalo M. Root canal preparation of mandibular molars with 3 nickel-titanium rotary instruments: a micro-computed tomographic study. J Endod. 2014; 40(11):1860-4.
36. West JD. The endodontic Glidepath: "Secret to rotary safety". Dent Today. 2010;29(9):86, 8, 90-3.
37. Grande NM, Castagnola R, Minciacchi I, Marigo L, Plotino G. A review of the latest developments in rotary NiTi technology and root canal preparation. Aust Dent J. 2023;68 Suppl 1:S24-s38.
38. Alvi Fatima HS, Arushi Goyal, Akshun S Gupta, Faiz Khan, Akanksha Sood. A literature review of single file NiTi rotary system in endodontics. IP Indian Journal of Conservative and Endodontics. 2021;6(2):85-7.
39. De-Deus G, Arruda TE, Souza EM, Neves A, Magalhães K, Thuanne E, et al. The ability of the Reciproc R25 instrument to reach the full root canal working length without a glide path. Int Endod J. 2013;46(10):993-8.
40. Shi L, Yang Y, Wan J, Xie W, Yang R, Yao Y. Shaping ability of rotary and reciprocating single-file systems in combination with and without different glide path techniques in simulated curved canals. J Dent Sci. 2022;17(4):1520-7.
41. Hage W, Zogheib C, Bukiet F, Sfeir G, Khalil I, Gergi R, et al. Canal Transportation and Centring Ability of Reciproc and Reciproc Blue With or Without Use of Glide Path Instruments: A CBCT Study. Eur Endod J. 2020;5(2):118-22.
42. Özyürek T, Yılmaz K, Uslu G. Shaping Ability of Reciproc, WaveOne GOLD, and HyFlex EDM Single-file Systems in Simulated S-shaped Canals. J Endod. 2017;43(5):805-9.
43. Bal EZ, Gunes B, Bayrakdar IS. Comparison of root canal shaping ability of different heat-treated NiTi single files: a micro-CT study. Quintessence Int. 2022;53(2):112-21.
44. D'Amario M, De Angelis F, Mancino M, Frascaria M, Capogreco M, D'Arcangelo C. Canal shaping of different single-file systems in curved root canals. J Dent Sci. 2017;12(4): 328-32.
45. Kim HC, Hwang YJ, Jung DW, You SY, Kim HC, Lee W. Micro-computed tomography and scanning electron microscopy comparisons of two nickel-titanium rotary root canal instruments used with reciprocating motion. Scanning. 2013;35(2):112-8.
46. Hwang YH, Bae KS, Baek SH, Kum KY, Lee W, Shon WJ, et al. Shaping ability of the conventional nickel-titanium and reciprocating nickel-titanium file systems: a comparative study using micro-computed tomography. J Endod. 2014;40(8):1186-9.
47. McRay B, Cox TC, Cohenca N, Johnson JD, Paranjpe A. A micro-computed tomography-based comparison of the canal transportation and centering ability of ProTaper Universal rotary and WaveOne reciprocating files. Quintessence Int. 2014;45(2):101-8.
48. Marceliano-Alves MF, Sousa-Neto MD, Fidel SR, Steier L, Robinson JP, Pécora JD, et al. Shaping ability of single-file reciprocating and heat-treated multifile rotary systems: a micro-CT study. Int Endod J. 2015;48(12):1129-36.

49. Gergi R, Osta N, Bourbouze G, Zgheib C, Arbab-Chirani R, Naaman A. Effects of three nickel titanium instrument systems on root canal geometry assessed by micro-computed tomography. Int Endod J. 2015;48(2):162-70.
50. Santa-Rosa J, de Sousa-Neto MD, Versiani MA, Nevares G, Xavier F, Romeiro K, et al. Shaping Ability of Single-file Systems with Different Movements: A Micro-computed Tomographic Study. Iran Endod J. 2016;11(3):228-33.
51. Venino PM, Citterio CL, Pellegatta A, Ciccarelli M, Maddalone M. A Micro-computed Tomography Evaluation of the Shaping Ability of Two Nickel-titanium Instruments, HyFlex EDM and ProTaper Next. J Endod. 2017;43(4):628-32.
52. Lacerda M, Marceliano-Alves MF, Pérez AR, Provenzano JC, Neves MAS, Pires FR, et al. Cleaning and Shaping Oval Canals with 3 Instrumentation Systems: A Correlative Micro-computed Tomographic and Histologic Study. J Endod. 2017;43(11):1878-84.
53. Versiani MA, Carvalho KKT, Mazzi-Chaves JF, Sousa-Neto MD. Micro-computed Tomographic Evaluation of the Shaping Ability of XP-endo Shaper, iRaCe, and EdgeFile Systems in Long Oval-shaped Canals. J Endod. 2018;44(3):489-95.
54. Bane K, Faye B, Sarr M, Niang SO, Ndiaye D, Machtou P. Root canal shaping by single-file systems and rotary instruments: a laboratory study. Iran Endod J. 2015;10(2):135-9.
55. Bartols A, Laux G, Walther W. Multiple-file vs. single-file endodontics in dental practice: a study in routine care. PeerJ. 2016;4:e2765.
56. Bürklein S, Schäfer E. Apically extruded debris with reciprocating single-file and full-sequence rotary instrumentation systems. J Endod. 2012;38(6):850-2.
57. Myers GL, Montgomery S. A comparison of weights of debris extruded apically by conventional filing and Canal Master techniques. J Endod. 1991;17(6):275-9.
58. Bürklein S, Benten S, Schäfer E. Quantitative evaluation of apically extruded debris with different single-file systems: Reciproc, F360 and OneShape versus Mtwo. Int Endod J. 2014;47(5):405-9.
59. Ozsu D, Karatas E, Arslan H, Topcu MC. Quantitative evaluation of apically extruded debris during root canal instrumentation with ProTaper Universal, ProTaper Next, WaveOne, and self-adjusting file systems. Eur J Dent. 2014;8(4):504-8.
60. Silva EJ, Carapiá MF, Lopes RM, Belladonna FG, Senna PM, Souza EM, et al. Comparison of apically extruded debris after large apical preparations by full-sequence rotary and single-file reciprocating systems. Int Endod J. 2016;49(7):700-5.
61. da Silva E, de Moura SG, de Lima CO, Barbosa AFA, Misael WF, Lacerda M, et al. Shaping ability and apical debris extrusion after root canal preparation with rotary or reciprocating instruments: a micro-CT study. Restor Dent Endod. 2021;46(2):e16.
62. Yılmaz K, Özyürek T. Apically Extruded Debris after Retreatment Procedure with Reciproc, ProTaper Next, and Twisted File Adaptive Instruments. J Endod. 2017;43(4):648-51.
63. Neves MA, Provenzano JC, Rôças IN, Siqueira JF, Jr. Clinical Antibacterial Effectiveness of Root Canal Preparation with Reciprocating Single-instrument or Continuously Rotating Multi-instrument Systems. J Endod. 2016;42(1):25-9.

64. Amaral RR, Love RM, Braga T, Souza Côrtes MI, Rachid C, Rôças IN, et al. Impact of root canal preparation using two single-file systems on the intra-radicular microbiome of teeth with primary apical periodontitis. Clin Oral Investig. 2024;28(2):139.
65. Machado ME, Nabeshima CK, Leonardo MF, Reis FA, Britto ML, Cai S. Influence of reciprocating single-file and rotary instrumentation on bacterial reduction on infected root canals. Int Endod J. 2013;46(11):1083-7.
66. Martinho FC, Gomes AP, Fernandes AM, Ferreira NS, Endo MS, Freitas LF, et al. Clinical comparison of the effectiveness of single-file reciprocating systems and rotary systems for removal of endotoxins and cultivable bacteria from primarily infected root canals. J Endod. 2014;40(5):625-9.
67. Üreyen Kaya B, Erik CE, Sesli Çetin E, Köle M, Maden M. Mechanical reduction in intracanal Enterococcus faecalis when using three different single-file systems: an ex vivo comparative study. Int Endod J. 2019;52(1):77-85.
68. Hamed SA, Shabayek S, Hassan HY. Biofilm elimination from infected root canals using four different single files. BMC Oral Health. 2022;22(1):660.
69. Sattapan B, Nervo GJ, Palamara JE, Messer HH. Defects in rotary nickel-titanium files after clinical use. J Endod. 2000;26(3):161-5.
70. de Vasconcelos RA, Murphy S, Carvalho CA, Govindjee RG, Govindjee S, Peters OA. Evidence for Reduced Fatigue Resistance of Contemporary Rotary Instruments Exposed to Body Temperature. J Endod. 2016;42(5):782-7.
71. Youssef E, Jungbluth H, Jepsen S, Gruener M, Bourauel C. Comparing Cyclic Fatigue Resistance and Free Recovery Transformation Temperature of NiTi Endodontic Single-File Systems Using a Novel Testing Setup. Materials (Basel). 2024;17(3).
72. Azim AA, Tarrosh M, Azim KA, Piasecki L. Comparison between Single-file Rotary Systems: Part 2-The Effect of Length of the Instrument Subjected to Cyclic Loading on Cyclic Fatigue Resistance. J Endod. 2018;44(12):1837-42.
73. Pedullà E, Grande NM, Plotino G, Gambarini G, Rapisarda E. Influence of continuous or reciprocating motion on cyclic fatigue resistance of 4 different nickel-titanium rotary instruments. J Endod. 2013;39(2):258-61.
74. Dagna A, Poggio C, Beltrami R, Colombo M, Chiesa M, Bianchi S. Cyclic fatigue resistance of OneShape, Reciproc, and WaveOne: An in vitro comparative study. J Conserv Dent. 2014;17(3):250-4.
75. da Frota MF, Espir CG, Berbert FL, Marques AA, Sponchiado-Junior EC, Tanomaru-Filho M, et al. Comparison of cyclic fatigue and torsional resistance in reciprocating single-file systems and continuous rotary instrumentation systems. J Oral Sci. 2014;56(4):269-75.
76. Kiefner P, Ban M, De-Deus G. Is the reciprocating movement per se able to improve the cyclic fatigue resistance of instruments? Int Endod J. 2014;47(5):430-6.
77. Al-Obaida MI, Alzuwayer AA, Alanazi SS, Balhaddad AA. In Vitro Analysis of the Fatigue Resistance of Four Single File Canal Preparation Instruments. Materials (Basel). 2022;15(2).

78. Neelakantan P, Reddy P, Gutmann JL. Cyclic fatigue of two different single files with varying kinematics in a simulated double-curved canal. J Investig Clin Dent. 2016;7(3): 272-7.
79. Bramante CM, Betti LV. Efficacy of Quantec rotary instruments for gutta-percha removal. Int Endod J. 2000;33(5):463-7.
80. Rios Mde A, Villela AM, Cunha RS, Velasco RC, De Martin AS, Kato AS, et al. Efficacy of 2 reciprocating systems compared with a rotary retreatment system for gutta-percha removal. J Endod. 2014;40(4):543-6.
81. Nevares G, de Albuquerque DS, Freire LG, Romeiro K, Fogel HM, Dos Santos M, et al. Efficacy of ProTaper NEXT Compared with Reciproc in Removing Obturation Material from Severely Curved Root Canals: A Micro-Computed Tomography Study. J Endod. 2016;42(5):803-8.
82. Özyürek T, Demiryürek E. Efficacy of Different Nickel-Titanium Instruments in Removing Gutta-percha during Root Canal Retreatment. J Endod. 2016;42(4):646-9.
83. Jorgensen B, Williamson A, Chu R, Qian F. The Efficacy of the WaveOne Reciprocating File System versus the ProTaper Retreatment System in Endodontic Retreatment of Two Different Obturating Techniques. J Endod. 2017;43(6):1011-3.
84. Delai D, Jardine AP, Mestieri LB, Boijink D, Fontanella VRC, Grecca FS, et al. Efficacy of a thermally treated single file compared with rotary systems in endodontic retreatment of curved canals: a micro-CT study. Clin Oral Investig. 2019;23(4):1837-44.
85. Abdelnaby P, Ibrahim M, ElBackly R. In vitro evaluation of filling material removal and apical debris extrusion after retreatment using Reciproc blue, Hyflex EDM and ProTaper retreatment files. BMC Oral Health. 2023;23(1):902.
86. Tantiwanichpun B, Kulvitit S. Efficiency and complications in root canal retreatment using nickel titanium rotary file with continuous rotation, reciprocating, or adaptive motion in curved root canals: a laboratory investigation. BMC Oral Health. 2023;23(1):871.
87. Ciftcioglu E, Sungur Guzel R, Akbal Dincer G, Karakaya G, Kucukay ES. Efficiency of ProTaper Universal Retreatment, Reciproc Blue and XP-endo Shaper in the removal of a bioceramic-based root canal filling. Eur Oral Res. 2023; 57(3):159-64.
88. Tocci L, Plotino G, Al-Sudani D, Rubini AG, Sannino G, Piasecki L, et al. Cutting efficiency of instruments with different movements: a comparative study. J Oral Maxillofac Res. 2015;6(1):e6.
89. Azim AA, Wang HH, Tarrosh M, Azim KA, Piasecki L. Comparison between Single-file Rotary Systems: Part 1-Efficiency, Effectiveness, and Adverse Effects in Endodontic Retreatment. J Endod. 2018;44(11):1720-4.