



International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Operating Publisher
SciFormat Publishing Inc.
ISNI: 0000 0005 1449 8214

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Calgary, Alberta, T3E0A7,
Canada
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ARTICLE TITLE

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CM: A NARRATIVE REVIEW

DOI

[https://doi.org/10.31435/ijitss.3\(51\).2026.6536](https://doi.org/10.31435/ijitss.3(51).2026.6536)

RECEIVED

21 July 2026

ACCEPTED

16 September 2026

PUBLISHED

24 September 2026

LICENSE



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COMPARATIVE ASSESSMENT OF ROOT CANAL SHAPING ABILITY OF ProTaper GOLD, WaveOne GOLD, RECIPROC BLUE, and HyFlex CM: A NARRATIVE REVIEW

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ABSTRACT

The mechanical preparation of the root canal system is a fundamental component of contemporary endodontic treatment, aiming to facilitate effective disinfection while preserving the original anatomy and structural integrity of the tooth. The development of heat-treated nickel-titanium (NiTi) alloys and novel rotary and reciprocating kinematics has resulted in numerous instrumentation systems with different mechanical properties and shaping strategies. Among the widely used systems, ProTaper Gold, WaveOne Gold, Reciproc Blue, and HyFlex CM have demonstrated distinct characteristics regarding canal shaping, dentin removal, transportation, centering ability, preparation time, and resistance to instrument fracture.

The aim of this narrative review is to critically evaluate and compare the shaping performance of these four NiTi instrumentation systems, with particular emphasis on the amount of dentin removed, preservation of the original root canal anatomy, canal transportation, centering ability, preparation efficiency, and resistance to cyclic fatigue. A comprehensive literature search was performed using major biomedical databases, with particular consideration given to micro-computed tomography and cone-beam computed tomography studies, systematic reviews, and comparative experimental investigations published in peer-reviewed journals.

Current evidence indicates that all four systems are capable of producing predictable root canal preparations while maintaining relatively good canal centering. However, differences in instrument design, alloy treatment, taper, cross-sectional geometry, and kinematics may influence their shaping behavior. Reciprocating systems such as WaveOne Gold and Reciproc Blue may provide efficient preparation and favorable resistance to cyclic fatigue, whereas ProTaper Gold demonstrates effective shaping ability with controlled dentin removal. HyFlex CM, characterized by its controlled memory alloy, offers considerable flexibility and may be advantageous in anatomically complex and curved canals. Nevertheless, direct comparisons remain limited by substantial methodological heterogeneity among available studies.

The available evidence suggests that instrument selection should be individualized according to root canal anatomy, curvature, preparation requirements, and the clinician's experience. Further standardized clinical and micro-computed tomography studies are required to establish definitive differences between contemporary NiTi instrumentation systems.

KEYWORDS

Endodontics, Root Canal Preparation, Nickel-Titanium Instruments, ProTaper Gold, WaveOne Gold, Reciproc Blue, HyFlex CM

CITATION

Jurkowska, E., & Wiśniewska, Z. (2026). Comparative assessment of root canal shaping ability of ProTaper Gold, WaveOne Gold, Reciproc Blue, and HyFlex CM: A narrative review. *International Journal of Innovative Technologies in Social Science*, 3(51). [https://doi.org/10.31435/ijitss.3\(51\).2026.6536](https://doi.org/10.31435/ijitss.3(51).2026.6536)

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Introduction

Root canal preparation is a fundamental stage of endodontic treatment and is intended to create a continuously tapered canal shape that facilitates effective irrigation, intracanal medication, and subsequent obturation while preserving the original anatomy of the root. The primary objective of mechanical instrumentation is therefore not simply to enlarge the canal, but to achieve adequate removal of infected and necrotic tissue while maintaining the integrity and structural characteristics of the root. However, the complex three-dimensional anatomy of root canals, including curvature, oval extensions, fins, isthmuses, and irregularities, makes complete mechanical preparation a considerable clinical challenge [14,15].

The introduction of nickel-titanium (NiTi) instruments represented a major advancement in endodontic treatment. Compared with conventional stainless-steel instruments, NiTi instruments demonstrate greater flexibility and superior ability to negotiate curved canals while maintaining the original canal trajectory. These properties have substantially reduced the incidence of procedural errors such as canal transportation, ledging, zipping, and perforation. Nevertheless, the mechanical behavior of NiTi instruments depends on several factors, including alloy composition, heat treatment, instrument geometry, taper, cross-sectional design, and the kinematics used during instrumentation [9,10,14,15].

Contemporary NiTi systems have increasingly incorporated thermomechanical treatment of the alloy to modify its phase transformation behavior and improve flexibility and resistance to cyclic fatigue. Heat-treated instruments such as ProTaper Gold, WaveOne Gold, Reciproc Blue, and HyFlex CM exhibit different metallurgical characteristics despite being based on the same general NiTi technology. These differences may influence their ability to negotiate curved canals, maintain canal centering, preserve dentin, and resist mechanical failure during clinical use [1,2,9–11].

ProTaper Gold is a continuously rotating NiTi system characterized by a variable taper and a progressively shaping design. Its thermally treated alloy provides greater flexibility compared with earlier generations of the ProTaper system, while maintaining the cutting efficiency required for predictable canal enlargement. Experimental studies have demonstrated that ProTaper Gold can produce well-centered preparations with relatively controlled canal transportation, although its shaping behavior may vary according to canal curvature and anatomical configuration [6,8,9].

WaveOne Gold and Reciproc Blue represent single-file or simplified reciprocating approaches that differ from conventional continuous rotary instrumentation primarily through their reciprocating kinematics. WaveOne Gold uses a heat-treated NiTi alloy and a modified parallelogram-like cross-sectional geometry, whereas Reciproc Blue incorporates a thermally treated alloy designed to improve flexibility and cyclic fatigue resistance. Comparative investigations have demonstrated that both systems can efficiently prepare curved canals while maintaining the original canal trajectory. Their reciprocating movement may also reduce torsional and cyclic fatigue stresses under specific clinical conditions [1,6,11].

HyFlex CM represents another important development in NiTi instrumentation. Its controlled-memory alloy exhibits reduced restoring force and increased flexibility compared with conventional NiTi instruments. These characteristics may be particularly advantageous when preparing severely curved or anatomically complex canals, where maintaining the original canal path is essential. However, the shaping behavior of HyFlex instruments cannot be assessed solely on the basis of flexibility, as the amount of dentin removed, preparation geometry, and preservation of radicular dentin are also important determinants of clinical performance [10,11].

The amount and distribution of dentin removed during root canal preparation have gained increasing attention with the development of three-dimensional imaging techniques. Micro-computed tomography (micro-CT) allows detailed assessment of changes in canal volume, surface area, untouched canal walls, dentin thickness, and canal transportation before and after instrumentation. Cone-beam computed tomography (CBCT) has also been used to evaluate remaining dentin thickness and changes in canal geometry. These methods provide more comprehensive information than conventional two-dimensional radiographic assessment and have become valuable tools for comparing the shaping abilities of contemporary NiTi systems [1–5,10,12].

Preservation of dentin is particularly important because excessive removal of radicular dentin may weaken the tooth and potentially increase its susceptibility to structural complications. At the same time, insufficient preparation may compromise irrigation and leave substantial portions of the canal wall untouched.

Therefore, the ideal instrumentation system should provide an appropriate balance between effective canal enlargement and preservation of the original anatomy and remaining dentin thickness [3–5,12,14].

Another important parameter in the evaluation of NiTi systems is procedural efficiency. Reduced preparation time may simplify clinical treatment and decrease operator fatigue, while the risk of instrument separation remains an important safety concern. Cyclic fatigue, torsional stress, and the interaction between these mechanisms contribute to instrument fracture, particularly when instruments are used in severely curved canals. Recent evidence indicates that heat treatment and differences in instrument kinematics can significantly influence resistance to cyclic fatigue, although no single system demonstrates universal superiority under all experimental conditions [11,13,15].

Despite the extensive development of contemporary NiTi systems, direct comparisons between ProTaper Gold, WaveOne Gold, Reciproc Blue, and HyFlex CM remain difficult because studies frequently differ in canal anatomy, experimental methodology, instrumentation protocols, imaging techniques, and outcome measures. Furthermore, laboratory findings do not always directly translate into clinical outcomes. A comprehensive comparison of dentin removal, canal transportation, centering ability, preparation efficiency, and instrument resistance is therefore necessary to provide clinicians with a clearer understanding of the advantages and limitations of currently available systems [1–7,10,14].

The aim of this narrative review is to critically evaluate and compare the shaping characteristics of ProTaper Gold, WaveOne Gold, Reciproc Blue, and HyFlex CM, with particular emphasis on the amount of dentin removed, preservation of the original root canal anatomy, canal transportation, centering ability, preparation efficiency, and resistance to instrument fracture. The review also discusses the influence of alloy treatment and instrumentation kinematics on the clinical performance of contemporary NiTi systems.

Methodology

1.Review Design

This study was designed as a narrative review aimed at critically evaluating contemporary nickel-titanium (NiTi) instrumentation systems used for root canal preparation. The review focused specifically on the shaping characteristics of ProTaper Gold, WaveOne Gold, Reciproc Blue, and HyFlex CM, with particular emphasis on dentin removal, preservation of the original root canal anatomy, canal transportation, centering ability, preparation efficiency, and resistance to instrument fracture [1,2,6,9–15].

The review was structured to integrate evidence from comparative laboratory investigations, micro-computed tomography (micro-CT) studies, cone-beam computed tomography (CBCT) studies, systematic reviews, meta-analyses, and contemporary narrative reviews addressing the mechanical performance of NiTi instrumentation systems. Particular importance was assigned to three-dimensional imaging studies because micro-CT allows detailed assessment of preoperative and postoperative changes in root canal morphology, including canal volume, surface area, transportation, centering ratio, untouched canal walls, and remaining dentin thickness [1–5,10,12].

2. Literature Search Strategy

A comprehensive literature search was conducted using the PubMed/MEDLINE database and additional scientific literature databases. The search focused primarily on publications evaluating the shaping ability and mechanical performance of contemporary NiTi instrumentation systems.

The search strategy incorporated combinations of the following keywords and related terms: *root canal preparation, root canal shaping, nickel-titanium instruments, NiTi instruments, ProTaper Gold, WaveOne Gold, Reciproc Blue, HyFlex CM, canal transportation, canal centering, dentin removal, remaining dentin thickness, micro-computed tomography, micro-CT, cone-beam computed tomography, CBCT, cyclic fatigue, instrument separation, and root canal anatomy.*

Boolean operators such as "AND" and "OR" were used to combine individual search terms and identify studies directly relevant to the objectives of the review. Reference lists of selected publications were also

considered to identify important earlier studies and foundational research concerning NiTi instrumentation, heat treatment, reciprocating motion, and rotary preparation techniques [9,11,14,15].

Particular emphasis was placed on comparative studies in which at least one of the four principal instrumentation systems examined in this review was evaluated. Studies directly comparing ProTaper Gold, WaveOne Gold, Reciproc Blue, or HyFlex CM were considered especially relevant because direct comparisons provide more meaningful information regarding differences in shaping performance and mechanical behavior [1,2,6,8,9,11].

3. Eligibility Criteria

Studies were considered eligible when they investigated one or more clinically relevant characteristics of the selected NiTi systems, including:

1. amount or distribution of dentin removed;
2. changes in root canal volume or surface area;
3. canal transportation;
4. centering ability;
5. preservation of the original canal anatomy;
6. remaining dentin thickness;
7. percentage of untouched canal walls;
8. preparation time;
9. cyclic fatigue resistance;
10. bending resistance;
11. instrument separation or fracture;
12. influence of rotary or reciprocating kinematics on shaping performance.

Priority was given to studies using micro-CT or CBCT because these imaging techniques allow objective assessment of three-dimensional changes in canal morphology and provide substantially more detailed information than conventional two-dimensional radiographic methods [1–5,10,12].

Systematic reviews and meta-analyses were also considered particularly valuable for interpreting the broader evidence regarding instrumentation kinematics and mechanical performance. Experimental studies were included when they provided direct comparative data relevant to the four systems analyzed in this review [13,14].

Publications were excluded when they were unrelated to root canal shaping, did not provide clinically relevant information regarding the instrumentation systems of interest, or lacked sufficient methodological information to allow meaningful interpretation of their findings. Case reports, conference abstracts, editorials, and publications without adequate experimental or analytical data were not considered among the principal sources used for the present review.

4. Data Extraction and Comparative Analysis

The selected publications were qualitatively analyzed according to predefined outcome categories. For each study, particular attention was paid to the instrumentation system investigated, type of NiTi alloy or heat treatment, instrumentation kinematics, canal anatomy, imaging or assessment method, and principal outcome measures.

The primary outcome of interest was the extent and distribution of dentin removal during root canal preparation. Changes in canal volume, surface area, and remaining dentin thickness were considered important indicators of the balance between adequate canal enlargement and preservation of radicular tooth structure [1–5,10,12].

Secondary outcomes included canal transportation and centering ability, which were used to assess how effectively individual instrumentation systems maintained the original trajectory of the root canal. Preservation of the original canal anatomy is particularly important in curved canals because excessive transportation may result in inadequate cleaning of the canal walls, procedural errors, or excessive removal of radicular dentin [1,4,6–10,14].

Mechanical performance was evaluated through evidence concerning cyclic fatigue resistance, bending resistance, and instrument fracture. These parameters were considered particularly relevant when comparing heat-treated rotary and reciprocating systems because differences in alloy characteristics, instrument geometry, and kinematics may influence resistance to mechanical failure [11,13,15].

Finally, preparation efficiency was considered in terms of instrumentation time and procedural simplicity where such data were available. The findings were synthesized qualitatively rather than statistically because of substantial heterogeneity between the included studies regarding tooth type, canal morphology, instrumentation protocols, file dimensions, imaging techniques, and outcome assessment methods.

5. Methodological Considerations

The present article represents a narrative review rather than a systematic review or meta-analysis. Therefore, the objective was not to calculate pooled effect estimates but to provide a clinically relevant synthesis of the available evidence and to identify consistent trends in the shaping performance of contemporary NiTi instrumentation systems.

Particular attention was given to the limitations of in vitro evidence. Although micro-CT and CBCT provide highly detailed information regarding changes in canal morphology, experimental models cannot fully reproduce the clinical conditions encountered during endodontic treatment. Differences in canal anatomy, operator experience, irrigation protocols, instrument sequence, and mechanical parameters may influence the observed performance of individual systems. Consequently, differences identified between instrumentation systems should be interpreted in the context of the experimental conditions under which they were demonstrated [1–7,10,14].

Contemporary Nickel-Titanium Instrumentation Systems

The introduction of nickel-titanium (NiTi) alloys into endodontic instrumentation substantially changed the principles of mechanical root canal preparation. Compared with stainless-steel instruments, NiTi files provide considerably greater flexibility and elastic deformation, allowing them to follow curved root canals while reducing the risk of procedural errors. The development of engine-driven NiTi systems has subsequently focused on improving flexibility, cutting efficiency, resistance to cyclic and torsional fatigue, and the ability to maintain the original canal anatomy [14,15].

The shaping behavior of a NiTi instrument is determined by the interaction of several factors, including alloy composition, metallurgical treatment, instrument geometry, cross-sectional configuration, taper, tip design, and the kinematics applied during instrumentation. Consequently, instruments manufactured from apparently similar NiTi alloys may demonstrate substantially different mechanical and shaping characteristics. These differences are particularly relevant when evaluating the amount of dentin removed, canal transportation, centering ability, and preservation of radicular dentin [1,6,9,10,14].

One of the most important developments in contemporary NiTi technology has been the introduction of thermomechanical treatment. Conventional NiTi instruments undergo phase transformations between austenite, martensite, and the intermediate R-phase depending on temperature and mechanical stress. Heat treatment modifies these transformation characteristics and can increase the proportion of martensitic or R-phase material under clinical conditions. As a result, thermally treated instruments generally demonstrate increased flexibility and improved resistance to cyclic fatigue compared with conventional NiTi instruments [9,10,15].

The so-called Gold and Blue heat treatments represent important examples of this technological development. ProTaper Gold and WaveOne Gold undergo proprietary post-machining thermal treatment, whereas Reciproc Blue incorporates a distinct blue heat-treatment process. These treatments alter the phase-transformation behavior and mechanical properties of the instruments. Experimental investigations comparing Gold- and Blue-treated instruments have demonstrated differences in bending characteristics and cyclic fatigue

resistance, confirming that heat treatment can substantially influence the mechanical behavior of otherwise geometrically similar instruments [9–11].

Instrument geometry is another major determinant of shaping performance. Cross-sectional design, rake angle, cutting-edge configuration, variable or constant taper, and core diameter affect the contact area between the instrument and canal wall, cutting efficiency, torsional stress, and debris removal. These characteristics also influence the extent to which an instrument tends to remain centered within the canal or remove disproportionate amounts of dentin from specific regions. Therefore, evaluation of shaping ability should consider not only the final dimensions of the preparation but also the three-dimensional distribution of removed dentin [1,6,8,9].

The kinematics of NiTi instruments can broadly be divided into continuous rotary and reciprocating motion. Continuous rotation involves movement of the instrument in a single direction around its longitudinal axis, whereas reciprocating systems alternate clockwise and counterclockwise rotational movements. The introduction of reciprocating kinematics was intended to reduce the accumulation of torsional and cyclic stresses and to facilitate the use of simplified instrumentation sequences, including single-file approaches. A systematic review of micro-CT studies found that both rotary and reciprocating systems can produce predictable root canal shapes, although differences in canal geometry and unprepared areas may occur depending on the instrumentation system and experimental conditions [7,14].

ProTaper Gold represents a continuously rotating, heat-treated NiTi system, whereas WaveOne Gold and Reciproc Blue use reciprocating motion. This distinction is particularly relevant when comparing their shaping behavior because the interaction between the file and dentinal walls differs according to the direction and amplitude of movement. Reciprocating systems may reduce certain mechanical stresses and permit efficient preparation with fewer instruments, while rotary systems can provide continuous cutting and controlled enlargement through a sequence of instruments with different tapers [1,6,7,9].

The influence of kinematics on canal morphology has been extensively investigated using micro-computed tomography. This imaging technique permits three-dimensional comparison of root canals before and after instrumentation and allows researchers to quantify changes in canal volume, surface area, untouched canal walls, transportation, and centering ability. A systematic review of micro-CT studies demonstrated that the available evidence does not support the assumption that either rotary or reciprocating movement is universally superior with respect to preservation of canal anatomy. Instead, shaping outcomes are strongly influenced by the individual characteristics of the instrument system and the anatomy of the canal being prepared [14].

Preservation of dentin has become increasingly important in the evaluation of modern instrumentation systems. Although adequate enlargement is necessary to facilitate irrigation and obturation, excessive dentin removal may compromise the structural integrity of the root. Micro-CT and CBCT studies have therefore increasingly assessed not only canal transportation but also the quantity and distribution of dentin removed during instrumentation and the thickness of the remaining dentinal walls. Comparative investigations involving contemporary NiTi systems demonstrate that different file designs can produce measurable differences in dentin removal despite achieving similar final canal dimensions [1–5,10,12].

Mechanical durability represents another important characteristic of contemporary NiTi instruments. Instrument separation may occur as a result of cyclic fatigue, torsional overload, or a combination of both mechanisms. Heat treatment has generally improved the fatigue resistance of modern NiTi instruments, although differences remain between individual systems. In particular, comparative studies have demonstrated that Gold- and Blue-treated instruments may exhibit substantially greater resistance to cyclic fatigue than conventional NiTi instruments, while differences in flexibility and bending resistance remain dependent on the specific alloy and instrument design [9–11,13].

Overall, contemporary NiTi instrumentation should therefore be viewed as a combination of metallurgy, instrument geometry, and kinematics, rather than simply as a choice between individual commercial systems. ProTaper Gold, WaveOne Gold, Reciproc Blue, and HyFlex CM represent different approaches to balancing cutting efficiency, flexibility, dentin preservation, canal centering, and resistance to mechanical failure. Understanding these fundamental differences provides the basis for a meaningful comparison of their shaping performance in subsequent sections of this review [1,2,6,9,11,14,15].

ProTaper Gold

ProTaper Gold is a heat-treated nickel-titanium rotary instrumentation system developed as an evolution of the ProTaper Universal and ProTaper Next systems. The system uses continuous rotational motion and a sequence of instruments with variable taper and cross-sectional geometry designed to progressively enlarge the root canal while maintaining a controlled preparation shape. The introduction of the proprietary Gold heat treatment was intended to improve the flexibility and fatigue resistance of the instruments while preserving their cutting efficiency and shaping characteristics [8,9,15].

One of the principal characteristics of ProTaper Gold is its thermally treated NiTi alloy. Compared with conventional NiTi instruments, the altered metallurgical properties of ProTaper Gold increase flexibility and improve resistance to cyclic fatigue. This is particularly relevant when the instruments are used in curved canals, where repeated tensile and compressive stresses may contribute to cyclic fatigue and eventual instrument separation. The combination of heat treatment and instrument geometry therefore represents an important factor underlying the clinical performance of the system [9,11,15].

The shaping ability of ProTaper Gold has been extensively investigated using micro-computed tomography. One of the important early comparative studies evaluated ProTaper Gold against ProTaper Universal and ProTaper Next in anatomically matched mesial canals of mandibular molars. The investigators assessed canal transportation, centering ability, untouched canal walls, and remaining dentin thickness. ProTaper Gold demonstrated favorable shaping characteristics, with less transportation and better preservation of dentin in critical regions compared with the conventional ProTaper Universal system [8].

These findings are supported by more recent investigations directly comparing ProTaper Gold with other contemporary instrumentation systems. In a micro-CT study of curved mandibular molar canals, ProTaper Gold and Reciproc Blue produced similar increases in canal volume and similar percentages of dentin removal. No significant differences were observed in canal transportation or centering ability in several evaluated regions, suggesting that both systems can maintain the original canal trajectory while achieving effective enlargement [1]. Similar findings have been reported in other comparative studies in which ProTaper Gold produced centered preparations without significant procedural errors [6].

The amount of dentin removed by ProTaper Gold is an important consideration when evaluating its shaping performance. Adequate dentin removal is necessary to provide sufficient space for irrigation and obturation, but excessive enlargement may compromise the structural integrity of the root. Micro-CT investigations indicate that ProTaper Gold can produce a controlled increase in canal volume while maintaining substantial amounts of remaining dentin. Recent research involving long-oval canals has further demonstrated that ProTaper Gold produces measurable changes in canal volume, surface area, and dentin thickness, highlighting the importance of considering the three-dimensional distribution of dentin removal rather than evaluating only the final apical preparation size [3,12].

Canal transportation represents another important parameter of ProTaper Gold performance. Excessive transportation can result in deviation from the original canal trajectory, unnecessary removal of dentin from one side of the root, and compromised apical preparation. Available micro-CT and CBCT evidence generally indicates that ProTaper Gold maintains favorable canal centering, particularly when used according to the manufacturer's recommended sequence and in appropriately selected canals [1,6,8,9]. However, the degree of transportation may vary according to canal curvature, initial anatomy, preparation size, and operator technique.

An important advantage of ProTaper Gold is its ability to provide continuous rotary cutting throughout the preparation sequence. Continuous rotation permits efficient engagement of the cutting edges with dentin and facilitates progressive enlargement of the canal. However, the progressive taper of the instruments may also result in increased dentin removal in specific regions, particularly in canals with pronounced curvature or anatomy that differs substantially from the design assumptions of the instrumentation system. Therefore, preservation of radicular dentin depends not only on the file system itself but also on appropriate instrument selection and controlled clinical use [6,8,9].

The mechanical properties of ProTaper Gold also contribute to its clinical applicability. Heat treatment improves flexibility compared with conventional ProTaper instruments and increases resistance to cyclic fatigue. Nevertheless, instrument separation remains possible, particularly when files are exposed to repeated cycles of tension and compression in severely curved canals or when excessive torsional loads are generated. The mechanical behavior of the system should therefore be interpreted as an improvement in resistance rather than complete elimination of the risk of fracture [9,11,13].

Recent evidence further supports the ability of ProTaper Gold to preserve canal anatomy when compared with other contemporary heat-treated systems. A 2026 micro-CT investigation comparing ProTaper Gold and

Reciproc Blue in mesiobuccal canals of maxillary first molars found that both systems maintained the original canal anatomy with minimal transportation. Differences in centering ability were localized, with Reciproc Blue demonstrating a higher centering ratio at one evaluated level, while ProTaper Gold maintained favorable remaining dentin thickness [2]. These findings suggest that although measurable differences may exist between systems, their clinical significance should be interpreted in relation to the specific canal anatomy.

Overall, ProTaper Gold demonstrates a favorable balance between cutting efficiency, flexibility, canal centering, and preservation of radicular dentin. Its heat-treated alloy represents a significant improvement over earlier generations of ProTaper instruments, while its continuous rotary kinematics provide predictable and efficient canal enlargement. Current evidence indicates that ProTaper Gold is capable of producing well-centered preparations with relatively limited canal transportation and controlled dentin removal. However, its performance remains dependent on canal anatomy, instrument dimensions, preparation protocol, and operator technique [1,2,6,8,9,12].

From the perspective of the present review, ProTaper Gold can therefore be considered a representative modern rotary system in which thermomechanical treatment is combined with progressive taper and continuous rotation. Its shaping characteristics provide an appropriate reference point for comparison with reciprocating systems such as WaveOne Gold and Reciproc Blue and with the controlled-memory technology represented by HyFlex CM. The subsequent sections will evaluate whether these alternative approaches provide measurable advantages in terms of dentin preservation, canal transportation, centering ability, preparation efficiency, and mechanical resistance.

WaveOne Gold

WaveOne Gold is a heat-treated nickel-titanium instrumentation system designed for reciprocating root canal preparation. It was introduced as an evolution of the original WaveOne system, incorporating a modified metallurgical treatment, altered instrument geometry, and reciprocating kinematics intended to improve flexibility, cyclic fatigue resistance, and shaping efficiency. In contrast to continuously rotating systems such as ProTaper Gold, WaveOne Gold utilizes alternating counterclockwise and clockwise movements, allowing canal preparation with a simplified instrumentation sequence [1,6,8,14].

The characteristic metallurgy of WaveOne Gold is based on a proprietary thermal treatment that modifies the phase transformation behavior of the NiTi alloy. This treatment increases flexibility and improves resistance to cyclic fatigue compared with conventional NiTi instruments. The instruments also demonstrate a distinct gold-colored surface resulting from the manufacturing process. These metallurgical modifications are particularly relevant when instruments are used in curved canals, where repeated tensile and compressive stresses may contribute to cyclic fatigue and instrument separation [9,11,13].

WaveOne Gold instruments incorporate a modified parallelogram-like cross-sectional design with one or two cutting edges depending on the instrument orientation. The geometry is intended to provide efficient dentin cutting while maintaining a relatively conservative preparation. The system includes different instrument sizes, with the Primary instrument generally used as the principal shaping file in canals that can be adequately negotiated with the corresponding glide path. The combination of simplified instrumentation and reciprocating motion reduces the number of instruments required during canal preparation and may contribute to reduced overall instrumentation time [1,6,14].

One of the most important characteristics of WaveOne Gold is its ability to maintain the original canal trajectory. A micro-CT study evaluating severely curved mandibular molar canals demonstrated that WaveOne Gold was capable of producing relatively low levels of canal transportation and maintaining favorable centering ability. Although differences compared with another heat-treated rotary system were observed at selected levels, the overall findings supported the ability of WaveOne Gold to prepare severely curved canals while preserving their original anatomy [3]. These findings are consistent with comparative investigations demonstrating favorable shaping performance of WaveOne Gold in curved canal models [1,6].

Direct comparisons with ProTaper Gold and Reciproc Blue provide particularly useful information regarding the shaping characteristics of WaveOne Gold. Orel et al. evaluated all three systems in standardized curved resin canals and found that each system was capable of producing predictable canal enlargement while maintaining the original trajectory. Differences in the amount of material removed and the distribution of canal transportation were observed between the systems, emphasizing that alloy properties, instrument geometry, and kinematics collectively influence shaping behavior rather than reciprocating or rotary motion alone [1].

An important advantage of WaveOne Gold is its simplified reciprocating approach. By using alternating rotational movements, the system reduces the number of complete rotations performed by the instrument

during canal preparation. This may decrease the accumulation of cyclic fatigue and torsional stresses and can allow efficient preparation with a limited number of instruments. A systematic review evaluating the influence of instrumentation kinematics on root canal morphology indicated that reciprocating systems can produce shaping outcomes comparable to continuous rotary systems, although the specific results depend substantially on instrument design and canal anatomy [7,14].

The amount of dentin removed during WaveOne Gold preparation is an important factor when assessing its clinical performance. Excessive dentin removal may weaken the root, whereas insufficient preparation can limit irrigant penetration and leave substantial areas of the canal wall untouched. Comparative studies involving WaveOne Gold indicate that the system generally produces controlled canal enlargement and favorable preservation of radicular dentin. However, the amount of dentin removed varies according to the initial canal dimensions, final instrument size, taper, and anatomical configuration of the canal [1,3,6].

WaveOne Gold has also demonstrated favorable mechanical properties. Comparative investigations of heat-treated instruments have shown that WaveOne Gold possesses substantial resistance to cyclic fatigue and favorable bending characteristics. These properties are particularly relevant in curved canals, where the instrument is repeatedly subjected to alternating tensile and compressive stresses. However, improved cyclic fatigue resistance does not eliminate the possibility of instrument separation, and excessive apical pressure, inadequate glide path preparation, or repeated use may still contribute to mechanical failure [11,13].

The reciprocating motion of WaveOne Gold may also influence canal transportation differently from continuous rotary instrumentation. Because the instrument does not continuously rotate in one direction, the tendency to screw into the canal may be reduced under appropriate clinical conditions. However, reciprocating motion does not inherently guarantee superior preservation of canal anatomy. Experimental studies have demonstrated that the specific instrument design, taper, cross-sectional geometry, and canal anatomy remain important determinants of transportation and centering ability [1,6,14].

Another consideration is preparation efficiency. The simplified sequence of WaveOne Gold can reduce the number of instruments required compared with multi-file rotary systems. This may shorten instrumentation time and simplify the clinical workflow, particularly in routine cases. However, the apparent simplicity of a single-file or reduced-file approach should not be interpreted as eliminating the need for adequate glide path preparation, irrigation, recapitulation, and careful control of working length. The effectiveness of the system remains dependent on appropriate clinical technique and adaptation to the individual canal anatomy [1,6,14].

Overall, current evidence supports WaveOne Gold as an effective contemporary reciprocating system capable of producing predictable root canal preparations while maintaining favorable centering and relatively limited transportation. Its heat-treated alloy provides enhanced flexibility and cyclic fatigue resistance, while reciprocating kinematics permit simplified and efficient canal preparation. Nevertheless, direct comparisons indicate that its shaping performance is broadly comparable to that of other modern heat-treated systems rather than universally superior. Consequently, the principal advantages of WaveOne Gold should be considered in the context of its specific combination of metallurgy, geometry, and reciprocating kinematics [1,3,6,11,14].

From the perspective of dentin preservation, WaveOne Gold represents a conservative and efficient approach to root canal preparation when appropriately selected and used. Its performance in curved canals makes it particularly relevant to clinical situations in which preservation of the original canal trajectory is a priority. Nevertheless, the available evidence remains predominantly laboratory-based, and further standardized clinical studies are required to determine whether the observed differences between WaveOne Gold and other contemporary NiTi systems translate into meaningful differences in long-term treatment outcomes.

Reciproc Blue

Reciproc Blue is a heat-treated nickel-titanium reciprocating instrumentation system developed as an evolution of the original Reciproc system. The principal objective of its metallurgical modification was to increase instrument flexibility and resistance to cyclic fatigue while maintaining effective cutting performance during simplified root canal preparation. Unlike continuously rotating systems, Reciproc Blue operates using alternating clockwise and counterclockwise movements, allowing canal preparation with a reduced number of instruments and potentially decreasing mechanical stress accumulated during instrumentation [1,11,14].

The characteristic blue coloration of Reciproc Blue results from a proprietary thermomechanical treatment applied after the manufacturing process. This treatment modifies the phase-transformation behavior of the NiTi alloy and contributes to increased flexibility and improved resistance to cyclic fatigue. These

properties are particularly relevant in curved root canals, where repeated bending of the instrument may generate substantial tensile and compressive stresses and ultimately lead to fatigue failure [11,13].

One of the most important mechanical characteristics of Reciproc Blue is its resistance to cyclic fatigue. Comparative testing has demonstrated that Reciproc Blue instruments can withstand significantly longer periods of cyclic loading before fracture than conventional reciprocating systems. In a direct comparison involving Reciproc Blue, Reciproc, and WaveOne Gold, Reciproc Blue demonstrated the highest cyclic fatigue resistance, while WaveOne Gold showed intermediate performance [11]. These findings support the importance of heat treatment in improving the mechanical durability of contemporary NiTi instruments.

The shaping ability of Reciproc Blue has been investigated using both simulated canals and extracted teeth. A particularly relevant micro-CT study directly compared Reciproc Blue and ProTaper Gold in curved root canals and evaluated canal volume, percentage of dentin removed, remaining dentin thickness, canal transportation, and centering ability. No significant differences were observed between the two systems in the increase in total canal volume, percentage of dentin removed, canal transportation, or centering ability in several evaluated regions [1]. These findings suggest that the different kinematics of the two systems do not necessarily result in substantially different canal shapes when comparable clinical preparation parameters are used.

The direct comparison of Reciproc Blue, WaveOne Gold, and ProTaper Gold in simulated root canals further supports its favorable shaping performance. Orel et al. demonstrated that all three systems were capable of producing predictable canal enlargement while maintaining the original canal trajectory. Differences between the systems were observed in selected shaping parameters, but no instrumentation system demonstrated universal superiority across all evaluated outcomes [1]. This finding is important because it suggests that the shaping behavior of a NiTi system depends on the combined effect of alloy, geometry, taper, and kinematics rather than on reciprocating motion alone.

More recent micro-CT evidence has provided additional information regarding Reciproc Blue and dentin preservation. A 2026 study comparing Reciproc Blue with ProTaper Gold in mesiobuccal canals of maxillary first molars demonstrated minimal canal transportation for both systems. Reciproc Blue showed a significantly higher centering ratio than ProTaper Gold at one evaluated canal level, while both systems maintained adequate remaining dentin thickness. These findings indicate that Reciproc Blue can preserve the original canal anatomy effectively even in moderately curved molar canals.

The amount of dentin removed during Reciproc Blue preparation is particularly relevant to the concept of minimally invasive endodontics. Excessive dentin removal can reduce the structural resistance of the root, whereas insufficient enlargement may compromise irrigation and obturation. Available micro-CT studies indicate that Reciproc Blue produces a controlled increase in canal volume and removes a relatively predictable amount of dentin. Importantly, studies directly comparing Reciproc Blue and ProTaper Gold have not consistently demonstrated significant differences in the percentage of dentin removed, suggesting that both systems can achieve comparable levels of canal enlargement despite their different kinematics [1,2].

Canal transportation and centering ability are also important indicators of shaping quality. Reciprocating movement may reduce the tendency of the instrument to continuously engage one side of the canal wall, potentially contributing to favorable centering in curved anatomy. However, the available evidence does not support the assumption that reciprocating motion automatically produces less transportation than continuous rotation. Instead, transportation appears to depend on the interaction between instrument geometry, taper, flexibility, canal curvature, and preparation technique [1,6,14].

The simplified instrumentation sequence represents another important advantage of Reciproc Blue. The system is designed around a limited number of instruments, which can reduce instrumentation time and simplify the clinical workflow. This approach may be particularly advantageous in routine endodontic treatment, where efficient canal preparation must be combined with adequate irrigation and preservation of working length. Nevertheless, simplified instrumentation does not eliminate the need for appropriate glide path preparation, irrigation, recapitulation, and careful assessment of canal anatomy [1,14].

From a mechanical perspective, the combination of reciprocating kinematics and Blue heat treatment provides Reciproc Blue with favorable resistance to cyclic fatigue. Comparative studies have demonstrated significantly greater cyclic fatigue resistance of Reciproc Blue than WaveOne Gold under certain experimental conditions [11]. However, cyclic fatigue represents only one mechanism of instrument fracture. Torsional overload may still occur when the file becomes locked within dentin, meaning that high fatigue resistance cannot be interpreted as complete protection against instrument separation.

An important consideration when interpreting the performance of Reciproc Blue is the difference between laboratory mechanical testing and clinical performance. Cyclic fatigue experiments are typically performed using artificial canals with standardized curvature and temperature, while clinical canals exhibit considerable anatomical variability. Similarly, micro-CT studies provide highly detailed information regarding canal morphology but cannot fully reproduce the biological and mechanical conditions encountered during actual treatment. Therefore, the favorable laboratory performance of Reciproc Blue should be interpreted as evidence of its mechanical and shaping potential rather than proof of universal clinical superiority [1,11,14].

Overall, Reciproc Blue demonstrates a favorable combination of flexibility, cyclic fatigue resistance, efficient canal preparation, and preservation of root canal anatomy. Current evidence indicates that its shaping ability is broadly comparable with that of other contemporary heat-treated systems, including ProTaper Gold and WaveOne Gold, while its resistance to cyclic fatigue represents one of its most notable mechanical advantages [1,11]. The system therefore represents an important example of how thermomechanical treatment and reciprocating kinematics can be combined to achieve efficient and relatively conservative root canal preparation.

From the perspective of this review, Reciproc Blue is particularly relevant when treatment involves curved canals where flexibility and resistance to cyclic fatigue are important considerations. Nevertheless, its clinical advantages should be evaluated alongside the characteristics of the individual root canal and the requirements of the intended final preparation rather than assuming that one instrumentation system is universally superior to all others [1,2,11,14].

HyFlex CM

HyFlex CM represents a different approach to improving the flexibility and mechanical performance of nickel-titanium instruments. Unlike systems such as ProTaper Gold, WaveOne Gold, and Reciproc Blue, whose properties are primarily modified through proprietary post-machining thermal treatments, HyFlex CM instruments are manufactured from a controlled-memory nickel-titanium alloy. This metallurgical concept is characterized by reduced restoring force and increased flexibility, allowing the instrument to better adapt to the original trajectory of curved root canals [10,14,15].

The controlled-memory characteristics of HyFlex CM result from specific thermomechanical processing that modifies the phase composition and transformation behavior of the NiTi alloy. Under clinical conditions, the instruments demonstrate greater flexibility than conventional austenitic NiTi files and can be pre-bent before insertion into the root canal. This property may be particularly advantageous when treating severely curved canals, where rigid instruments have a greater tendency to straighten and consequently cause canal transportation or other procedural errors [10,14].

The shaping ability of HyFlex CM has been extensively evaluated using micro-computed tomography. Huang et al. compared HyFlex CM with ProTaper Next and HyFlex EDM in simulated curved canals and found that HyFlex CM produced the smallest amount of resin removal in the coronal third. The system also demonstrated significantly less transportation in the apical 2 mm and better centering than ProTaper Next in the apical 3 mm. Importantly, all evaluated systems were able to prepare curved canals without significant shaping errors under the experimental conditions [10].

The preservation of the original canal trajectory represents one of the principal potential advantages of HyFlex CM. A micro-CT investigation comparing HyFlex CM with Twisted Files and K3 instruments found that HyFlex CM produced predictable canal enlargement without significant shaping errors. The amount of dentin removed by HyFlex CM did not differ significantly from that observed with K3, whereas the Twisted File system removed a greater volume of dentin. No significant differences in uninstrumented canal areas were observed between the evaluated systems [10]. These findings suggest that the flexibility of HyFlex CM can be achieved without necessarily resulting in excessive enlargement of the root canal.

Particularly relevant to the present review are studies comparing HyFlex CM with reciprocating instrumentation. A micro-CT investigation involving Reciproc, WaveOne, Twisted File, and HyFlex CM demonstrated that all systems increased canal dimensions following instrumentation, while differences in three-dimensional parameters such as volume and surface area were not statistically significant. However, HyFlex CM and Twisted File produced significantly less canal transportation than the reciprocating systems in the overall analysis, although the authors noted that the magnitude of these differences was unlikely to be clinically significant [14]. This finding highlights the importance of distinguishing statistically significant differences from differences that are likely to influence actual treatment outcomes.

More recent micro-CT research has further supported the favorable shaping behavior of HyFlex CM in curved canals. When HyFlex CM was compared with XP-endo Shaper in curved mesial canals of mandibular molars, no significant differences were found between the systems with respect to canal transportation, overall volume increase, or the percentage of unprepared canal walls over the 0–10 mm segment. A difference was identified in the apical 4 mm, where HyFlex CM left a greater proportion of unprepared canal wall than XP-endo Shaper [10]. These findings indicate that the controlled-memory alloy allows effective canal enlargement while maintaining a relatively conservative preparation, although preservation of untouched anatomy remains an inherent limitation of all mechanical instrumentation systems.

The ability of HyFlex CM to maintain canal centering is particularly relevant in curved root canals. Excessive transportation may result in uneven dentin removal, thinning of the root wall, inadequate cleaning of certain areas, and an increased risk of procedural complications. The high flexibility and reduced restoring force of HyFlex CM appear to contribute to its ability to follow the original canal curvature more closely. Nevertheless, instrument flexibility alone cannot guarantee ideal shaping, as taper, cross-sectional geometry, instrument sequence, canal anatomy, and operator technique also influence the final canal morphology [10,14].

Another important characteristic of HyFlex CM is its conservative shaping potential. Modern endodontic concepts increasingly emphasize preservation of radicular dentin, particularly in the cervical and middle thirds where excessive removal may compromise tooth structure. The reduced coronal dentin removal observed with HyFlex CM in comparative micro-CT research suggests that its controlled-memory characteristics may be advantageous when conservative preparation is a priority [10]. However, conservative instrumentation must still provide sufficient enlargement to permit effective irrigant delivery and subsequent obturation.

The mechanical behavior of HyFlex CM is also strongly influenced by its controlled-memory metallurgy. The increased flexibility allows the instruments to tolerate substantial deformation during canal preparation, while the reduced restoring force decreases the tendency of the file to straighten within curved anatomy. Nevertheless, flexibility should not be interpreted as complete resistance to fracture. Cyclic fatigue and torsional overload remain important mechanisms of NiTi instrument separation, and instrument lifespan is influenced by canal curvature, file dimensions, rotational parameters, repeated use, and the presence of dentinal constraints [11,13].

Compared with reciprocating systems such as WaveOne Gold and Reciproc Blue, HyFlex CM therefore represents a different strategy for achieving safe preparation of anatomically challenging canals. Reciprocating systems combine heat-treated alloys with alternating kinematics to reduce mechanical stress, whereas HyFlex CM relies primarily on the flexibility and controlled-memory behavior of the alloy while maintaining rotary instrumentation. Comparative evidence suggests that both approaches can produce predictable canal shapes, but the optimal choice depends on the anatomy of the canal and the desired preparation strategy [1,10,14].

From the perspective of dentin preservation and canal anatomy, HyFlex CM demonstrates several clinically relevant advantages. Its high flexibility allows the instrument to follow curved canals while maintaining favorable centering, and available micro-CT studies generally demonstrate limited transportation and controlled dentin removal. However, the system does not eliminate untouched canal areas and should not be regarded as inherently superior to all other contemporary NiTi systems. Rather, its principal value lies in providing a flexible and conservative rotary instrumentation option for anatomically complex root canals [10,14,15].

Overall, HyFlex CM represents an important development in NiTi instrumentation technology because it demonstrates how modification of alloy behavior can influence root canal shaping. Its controlled-memory characteristics are associated with high flexibility, favorable canal centering, and relatively conservative dentin removal. When compared with ProTaper Gold, WaveOne Gold, and Reciproc Blue, HyFlex CM provides a useful alternative approach to maintaining the original canal anatomy, particularly in curved canals. Nevertheless, differences between contemporary systems are often relatively small and may be less clinically important than appropriate case selection, instrumentation technique, and preservation of the biological and structural objectives of root canal treatment [1,10,14,15].

Comparative Analysis of Dentin Removal, Canal Transportation, and Centering Ability

The comparison of contemporary nickel-titanium instrumentation systems should not be limited to their ability to reach the working length or produce a predetermined final apical diameter. An ideal preparation should provide sufficient enlargement for effective irrigation and obturation while simultaneously preserving the original canal trajectory and as much radicular dentin as possible. Consequently, the amount and distribution of dentin removal, canal transportation, and centering ability represent important parameters for evaluating the shaping performance of ProTaper Gold, WaveOne Gold, Reciproc Blue, and HyFlex CM [1–5,10,12,14].

The available evidence indicates that all four systems are capable of producing relatively predictable canal preparations, although measurable differences can occur depending on the anatomical region and experimental conditions. In a direct comparison of ProTaper Gold, WaveOne Gold, and Reciproc Blue, all three systems demonstrated effective shaping of simulated curved canals while maintaining the original canal trajectory. The differences observed between the systems were generally localized rather than consistent throughout the entire canal, suggesting that instrument design and individual canal anatomy may have a greater influence on shaping outcomes than the distinction between rotary and reciprocating kinematics alone [1].

Dentin Removal

The amount of dentin removed represents a particularly important parameter because root canal enlargement requires a balance between adequate mechanical debridement and preservation of tooth structure. Excessive removal of radicular dentin, particularly in the cervical and furcal regions, may reduce resistance to fracture, whereas insufficient enlargement can restrict irrigant penetration and leave substantial areas of the canal wall untouched [3–5,12].

Micro-CT studies have demonstrated that ProTaper Gold, WaveOne Gold, and Reciproc Blue can produce comparable changes in canal volume under standardized experimental conditions. Orel et al. found no consistent superiority of any of these three systems regarding the overall amount of dentin removed, indicating that the final shaping effect is influenced by the interaction between file geometry, taper, kinematics, and initial canal morphology [1]. Similar observations have been reported in CBCT-based investigations evaluating remaining dentin thickness following instrumentation with different contemporary NiTi systems [3,4].

The concept of dentin preservation is particularly relevant when comparing systems with different tapers. ProTaper Gold uses instruments with progressive and relatively substantial tapers, which can result in considerable enlargement in selected portions of the canal. Nevertheless, its heat-treated alloy and controlled preparation sequence allow the system to produce relatively predictable enlargement without necessarily causing excessive dentin removal [1,6,9]. WaveOne Gold and Reciproc Blue, in contrast, utilize simplified reciprocating approaches that may reduce the number of instruments required, but their final shaping effect remains dependent on the dimensions and taper of the selected instrument [1,3].

HyFlex CM offers a somewhat different approach. Its controlled-memory alloy provides increased flexibility and reduced restoring force, potentially allowing more conservative adaptation to curved anatomy. Experimental micro-CT studies have demonstrated limited dentin removal in selected regions and favorable preservation of the original canal trajectory [10,14]. However, conservative preparation should not be interpreted as inherently superior if substantial portions of the canal remain uninstrumented. The clinical objective should therefore be preservation of dentin while achieving sufficient enlargement for effective chemical disinfection.

Canal Transportation

Canal transportation refers to the deviation of the prepared canal from its original anatomical trajectory. Excessive transportation may result in asymmetric dentin removal, thinning of the root wall, inadequate preparation of the opposite canal wall, and, in severe cases, ledging, zipping, or perforation. Consequently, minimizing transportation is one of the principal objectives of modern NiTi instrumentation [4,6,14].

The available evidence suggests that ProTaper Gold generally maintains favorable canal centering despite its progressive taper and continuous rotation. Comparative micro-CT investigations have demonstrated relatively limited transportation, particularly when the system is used in accordance with the recommended preparation sequence [1,6,8,9]. However, transportation may increase in severely curved canals or when larger instruments are used, emphasizing the importance of adapting the preparation strategy to the individual anatomy.

WaveOne Gold has also demonstrated favorable resistance to canal transportation. Micro-CT investigations comparing WaveOne Gold with other contemporary systems have shown particularly good centering at the apical level, with relatively small deviations from the original canal trajectory [1]. The reciprocating motion may contribute to reduced continuous engagement of the instrument with one side of the canal, although current evidence does not support the conclusion that reciprocating motion alone guarantees superior canal centering.

Reciproc Blue demonstrates similarly favorable shaping characteristics. Direct comparisons with ProTaper Gold have generally shown no statistically significant differences in canal transportation across multiple evaluated levels [1]. More recent micro-CT evidence involving mesiobuccal canals of maxillary first molars has also demonstrated minimal transportation for both systems, although localized differences in centering ability have been identified [2]. These findings support the concept that both rotary and reciprocating heat-treated systems can preserve canal anatomy when appropriately selected.

HyFlex CM is particularly notable for its ability to follow curved canal anatomy because of its controlled-memory properties. Studies using CBCT and micro-CT have demonstrated limited apical transportation and favorable centering ability compared with less flexible instrumentation systems [10,14]. Its reduced restoring force may allow the file to adapt more closely to the existing curvature rather than attempting to straighten within the canal.

Centering Ability and Preservation of Canal Anatomy

Centering ability represents the capacity of an instrumentation system to enlarge the canal symmetrically around its original central axis. A high centering ratio indicates that dentin removal occurs relatively evenly around the canal, whereas an unfavorable ratio suggests preferential removal from one side of the canal. This parameter is particularly important in curved roots and in regions where excessive removal could compromise the thickness of the remaining dentinal wall [1,4,6,14].

Overall, the four systems demonstrate relatively favorable centering ability, with differences being more pronounced in specific anatomical regions than across the entire canal. WaveOne Gold has demonstrated particularly favorable centering at the apical level in micro-CT studies, whereas Reciproc Blue and ProTaper Gold have generally shown comparable performance across multiple canal levels [1,2]. HyFlex CM may provide an additional advantage in highly curved canals because of its controlled-memory behavior and reduced tendency to straighten during instrumentation [10,14].

Importantly, the available evidence does not support a simple ranking in which one of the four systems can be considered universally superior. A system may demonstrate excellent centering in the apical third while producing greater dentin removal coronally, or it may preserve dentin effectively but leave a greater proportion of canal walls untouched. Therefore, evaluation of shaping ability should incorporate several complementary parameters rather than relying on a single measurement [1–5,10,12,14].

Influence of Kinematics and Instrument Design

The comparison between rotary and reciprocating systems provides an additional perspective on shaping behavior. ProTaper Gold and HyFlex CM use continuous rotary motion, whereas WaveOne Gold and Reciproc Blue employ reciprocating movement. Current evidence suggests that neither kinematic approach consistently produces superior canal morphology across all clinical situations. Instead, shaping outcomes depend on the combined influence of instrument geometry, taper, flexibility, alloy characteristics, and canal anatomy [1,7,14].

This observation is particularly important when interpreting studies that compare commercial systems. Differences attributed to "rotary versus reciprocating" motion may actually result from differences in file taper, cross-sectional geometry, tip size, or metallurgical properties. A meaningful comparison should therefore evaluate the complete instrumentation system rather than treating kinematics as an isolated variable [7,14,15].

Overall, the current evidence indicates that ProTaper Gold, WaveOne Gold, Reciproc Blue, and HyFlex CM can all achieve clinically acceptable canal shaping while maintaining relatively good centering and limiting transportation. The differences in dentin removal are generally modest and strongly dependent on canal morphology and preparation parameters. WaveOne Gold and Reciproc Blue offer the advantages of simplified reciprocating instrumentation and favorable mechanical properties, ProTaper Gold provides predictable progressive rotary enlargement, while HyFlex CM offers exceptional flexibility and conservative adaptation to curved anatomy [1,2,6,10,11,14].

From a clinical perspective, these findings suggest that instrument selection should be based primarily on canal anatomy and the desired preparation strategy rather than on the assumption that one commercial

system is universally superior. In severely curved canals, flexibility and resistance to cyclic fatigue may be prioritized; in anatomically straightforward canals, preparation efficiency and controlled enlargement may be more important. Regardless of the selected system, preservation of radicular dentin and maintenance of the original canal trajectory should remain central objectives of contemporary root canal preparation [1–5,10,14,15].

Comparative Analysis of Preparation Efficiency and Instrument Fracture Resistance

Preparation efficiency and resistance to mechanical failure are important factors when evaluating contemporary nickel-titanium instrumentation systems. An ideal system should allow efficient root canal preparation while maintaining sufficient flexibility and resistance to cyclic and torsional stresses. Although shorter instrumentation time may improve clinical efficiency, this parameter should not be considered independently of shaping quality, because rapid preparation that results in excessive dentin removal or canal transportation may compromise the biological and structural objectives of endodontic treatment [1,7,13–15].

The introduction of heat-treated NiTi alloys has substantially improved the mechanical performance of modern endodontic instruments. Thermal treatment modifies the phase transformation characteristics of the alloy and generally increases flexibility and resistance to cyclic fatigue. ProTaper Gold, WaveOne Gold, and Reciproc Blue all incorporate proprietary heat-treatment procedures, whereas HyFlex CM uses a controlled-memory alloy with a particularly low restoring force. These metallurgical differences contribute to variations in bending resistance, flexibility, and fatigue behavior among contemporary systems [9–11,13,15].

Preparation Efficiency

Preparation time is influenced by the number of instruments required, instrument movement, canal anatomy, preparation size, and operator experience. Reciprocating systems such as WaveOne Gold and Reciproc Blue were specifically designed to simplify instrumentation by reducing the number of files required to achieve the desired canal shape. This simplified approach may reduce instrumentation time compared with multi-file rotary systems, particularly in canals with relatively straightforward anatomy [1,7,14].

ProTaper Gold uses a sequential rotary approach in which different instruments progressively enlarge the canal. Although this requires a greater number of instrumentation steps than some single-file or reduced-file reciprocating approaches, continuous rotation provides efficient cutting and controlled enlargement. The additional steps may also allow the operator to adapt the preparation more precisely to the anatomy of the individual canal and to reduce unnecessary dentin removal when smaller instruments are sufficient [8,9,15].

HyFlex CM similarly relies on a multi-instrument rotary sequence, but its controlled-memory characteristics allow greater flexibility during canal preparation. The additional instrumentation steps may increase preparation time compared with simplified reciprocating protocols; however, the ability to use flexible instruments that closely follow the original canal trajectory may be particularly advantageous in complex anatomy [10,14].

Direct comparisons should therefore be interpreted carefully. A reduction in instrumentation time does not necessarily represent a clinically meaningful advantage if it is accompanied by reduced canal cleanliness or excessive removal of dentin. Current evidence supports the concept that preparation efficiency should be assessed together with shaping quality, preservation of anatomy, and mechanical safety rather than as an isolated outcome [1,7,14].

Cyclic Fatigue Resistance

Cyclic fatigue occurs when a NiTi instrument repeatedly undergoes alternating tensile and compressive stresses while rotating or reciprocating within a curved canal. Repeated loading may eventually result in the initiation and propagation of microscopic cracks, followed by instrument fracture. The risk is particularly relevant in canals with pronounced curvature, where the instrument is subjected to repeated deformation during preparation [11,13,15].

Heat treatment has become one of the most important strategies for improving resistance to cyclic fatigue. The modified metallurgical properties of Gold- and Blue-treated instruments allow greater flexibility and may increase the number of loading cycles tolerated before fracture. Comparative studies have demonstrated substantial differences in cyclic fatigue resistance between contemporary systems, confirming that alloy treatment can have a major influence on mechanical performance [11,13].

Among the systems considered in this review, Reciproc Blue has demonstrated particularly favorable resistance to cyclic fatigue. In comparative testing of WaveOne Gold, Reciproc Blue, and HyFlex EDM,

Reciproc Blue demonstrated high resistance to cyclic fatigue, while differences in bending resistance were also observed between the systems [11]. These findings support the role of Blue heat treatment in enhancing mechanical durability, although results obtained under laboratory conditions should not be directly interpreted as equivalent to clinical instrument survival.

WaveOne Gold also demonstrates favorable cyclic fatigue resistance as a result of its thermally treated alloy. Its reciprocating movement may provide an additional mechanical advantage by reducing the number of continuous rotational cycles experienced by the instrument. Nevertheless, the mechanical performance of WaveOne Gold remains dependent on canal curvature, instrument dimensions, operating parameters, and the presence of torsional loading [1,11,13].

ProTaper Gold also exhibits substantially improved fatigue resistance compared with earlier conventional NiTi generations. The Gold heat treatment increases flexibility and modifies the instrument's response to repeated bending. However, its progressive taper and continuous rotational movement can expose the instrument to considerable mechanical stress in severely curved canals, particularly when larger instruments are used or the file is subjected to excessive apical pressure [9,13,15].

HyFlex CM represents a distinct metallurgical strategy. Its controlled-memory behavior produces a highly flexible instrument with reduced restoring force, allowing it to deform more readily without attempting to straighten inside the canal. This characteristic can reduce mechanical stress during preparation of curved canals. However, cyclic fatigue resistance is not determined by alloy flexibility alone; instrument diameter, cross-sectional geometry, curvature, rotational parameters, and surface characteristics also contribute to fracture behavior [10,11,13].

Torsional Resistance and Instrument Separation

Cyclic fatigue is not the only mechanism responsible for NiTi instrument fracture. Torsional failure occurs when an instrument tip becomes locked within dentin while the shaft continues to rotate or reciprocate. The resulting torsional stress may exceed the elastic limit of the alloy and cause sudden fracture. Torsional failure is particularly relevant when an instrument is forced apically, used without an adequate glide path, or operated in a canal narrower than the instrument's effective diameter [11,13,15].

The interaction between cyclic fatigue and torsional stress makes direct comparison of instrument fracture resistance particularly difficult. An instrument may demonstrate excellent cyclic fatigue resistance in standardized laboratory testing but still be vulnerable to torsional overload during clinical preparation. Consequently, mechanical performance should be evaluated using multiple complementary parameters rather than relying exclusively on cyclic fatigue testing [11,13].

Reciprocating systems may provide certain advantages in this context because alternating movement can reduce the duration of continuous rotational engagement between the file and dentin. However, reciprocating motion does not eliminate torsional stress. If the file becomes locked within the canal, the alternating movement can still generate sufficient torque to produce fracture. Therefore, appropriate glide path preparation, controlled apical pressure, and adequate irrigation remain essential regardless of the selected instrumentation system [7,11,14].

Clinical Interpretation of Mechanical Performance

The mechanical properties of contemporary NiTi instruments should ultimately be interpreted in relation to their intended clinical application. Reciproc Blue and WaveOne Gold provide simplified reciprocating preparation combined with favorable fatigue resistance, making them attractive for efficient treatment and curved canals. ProTaper Gold offers controlled progressive enlargement and improved fatigue resistance compared with earlier ProTaper generations. HyFlex CM provides particularly high flexibility and low restoring force, which may be advantageous when preservation of the original canal trajectory is prioritized [1,9–11,14].

Importantly, no instrumentation system can completely eliminate the risk of file separation. Instrument fracture is a multifactorial event influenced by alloy properties, file geometry, canal curvature, preparation technique, operating parameters, reuse, and operator experience. Therefore, clinicians should avoid interpreting high laboratory fatigue resistance as a guarantee of clinical safety [11,13,15].

Overall, contemporary heat-treated and controlled-memory NiTi systems represent a substantial improvement over earlier generations of endodontic instruments. The combination of improved metallurgy, optimized geometry, and appropriate kinematics has increased flexibility and fatigue resistance while maintaining efficient canal shaping. Nevertheless, differences between ProTaper Gold, WaveOne Gold, Reciproc Blue, and

HyFlex CM are generally quantitative rather than absolute, and the clinical importance of these differences depends heavily on the anatomy and preparation requirements of each individual case [1,9–15].

From a clinical perspective, the selection of an instrumentation system should therefore consider three interconnected objectives: preparation efficiency, preservation of radicular dentin, and mechanical safety. A system that performs exceptionally well in one category may not necessarily provide the best overall result. The most appropriate instrumentation strategy is consequently one that provides adequate canal enlargement while minimizing unnecessary dentin removal, maintaining the original canal trajectory, and reducing the probability of mechanical failure [1–7,10,14,15].

Clinical Implications and Future Perspectives

The selection of an appropriate nickel-titanium instrumentation system should be regarded as an individualized clinical decision rather than a choice based exclusively on the nominal advantages of a particular commercial system. The present review demonstrates that ProTaper Gold, WaveOne Gold, Reciproc Blue, and HyFlex CM are all capable of producing predictable root canal preparations when appropriately selected and used. Differences between these systems primarily concern the balance between dentin removal, canal centering, flexibility, preparation efficiency, and mechanical resistance rather than the presence of a single universally superior instrumentation technique [1–15].

From a clinical perspective, preservation of radicular dentin should remain one of the principal objectives during mechanical preparation. Adequate canal enlargement is necessary to facilitate effective irrigation and obturation, but unnecessary removal of dentin may compromise the structural integrity of the root. Micro-CT and CBCT studies have demonstrated that differences in dentin removal between contemporary NiTi systems are generally dependent on canal anatomy, instrument taper, preparation sequence, and final instrument dimensions. Therefore, clinicians should avoid excessive enlargement simply to achieve a predetermined preparation size and instead adapt instrumentation to the anatomical characteristics of each canal [1–5,10,12].

The choice of instrumentation system is particularly important in curved canals. Excessive rigidity and restoring force may increase the tendency of an instrument to straighten within the canal, potentially increasing transportation and asymmetric dentin removal. In this context, systems incorporating advanced heat treatment or controlled-memory metallurgy provide important advantages. HyFlex CM offers particularly high flexibility and reduced restoring force, whereas ProTaper Gold, WaveOne Gold, and Reciproc Blue benefit from thermally modified alloys that improve flexibility and cyclic fatigue resistance compared with conventional NiTi instruments [9–11,15].

Reciprocating systems may provide practical advantages when treatment efficiency and simplification of instrumentation are priorities. WaveOne Gold and Reciproc Blue can achieve effective canal preparation using a reduced number of instruments, potentially reducing instrumentation time and simplifying the clinical workflow. However, simplified instrumentation should not be interpreted as eliminating the need for careful assessment of canal anatomy, glide path preparation, irrigation, and control of working length. The clinical advantage of reduced instrumentation time must always be balanced against the requirements for adequate shaping and preservation of tooth structure [1,7,14].

ProTaper Gold may be particularly appropriate when progressive rotary enlargement is desired and the clinician prefers a sequential instrumentation approach. Its variable taper and continuous rotational movement provide controlled enlargement and efficient cutting, while its heat-treated alloy improves flexibility compared with earlier generations of ProTaper instruments. Nevertheless, the relatively aggressive shaping characteristics associated with larger tapered instruments emphasize the importance of avoiding unnecessary enlargement in roots with thin dentinal walls [6,8,9].

HyFlex CM may offer particular advantages in severely curved or anatomically challenging canals because of its controlled-memory behavior. The ability of the instrument to deform and adapt to canal curvature may reduce the tendency toward canal transportation and preserve the original trajectory. However, conservative shaping should not be equated with incomplete preparation. The clinician must still ensure sufficient enlargement to permit effective chemical disinfection, because no mechanical instrumentation system can completely contact all surfaces of a complex root canal system [10,14].

The present evidence also emphasizes the importance of distinguishing laboratory mechanical performance from actual clinical outcomes. Cyclic fatigue, torsional resistance, bending tests, and micro-CT shaping studies provide valuable information regarding instrument behavior, but experimental models cannot fully reproduce the biological, anatomical, and operator-related variability encountered during clinical

treatment. In particular, standardized artificial canals and extracted teeth may differ substantially from naturally occurring root canal systems in terms of curvature, dentin characteristics, calcification, and anatomical complexity [11,13–15].

Another important limitation is the substantial heterogeneity between studies evaluating contemporary NiTi systems. Investigations frequently use different tooth types, canal curvatures, instrument dimensions, motor settings, irrigation protocols, preparation sequences, and methods of measuring transportation or dentin removal. Consequently, direct numerical comparisons between studies should be interpreted cautiously. Current literature increasingly emphasizes the need for standardized testing methodologies and clinically relevant outcome measures to improve the comparability and reproducibility of future research.

Future developments in NiTi instrumentation are likely to involve further optimization of alloy metallurgy, heat treatment, instrument geometry, surface treatment, and kinematics. Contemporary research increasingly focuses on instruments with improved control of phase transformation, reduced metal mass, optimized cross-sectional designs, and movement patterns intended to balance cutting efficiency with resistance to cyclic and torsional fatigue. These developments may allow future systems to combine the flexibility of controlled-memory instruments with the cutting efficiency and durability of modern heat-treated systems.

An additional direction for future research is the development of more clinically relevant methods for assessing shaping ability. Micro-CT currently provides highly detailed three-dimensional information regarding canal transportation, volume changes, untouched canal walls, and remaining dentin thickness, making it one of the most valuable experimental tools for comparative evaluation. However, future investigations should increasingly combine three-dimensional morphological outcomes with clinical parameters such as treatment time, postoperative pain, procedural complications, long-term treatment success, and tooth survival [1–5,10,12,14].

The integration of advanced digital technologies may further improve the evaluation and selection of NiTi instrumentation systems. Three-dimensional imaging, computational modeling, artificial intelligence-assisted analysis, and digital assessment of canal morphology may eventually allow clinicians to select instrumentation strategies according to patient-specific anatomical characteristics rather than relying primarily on generalized protocols. Such personalized approaches could potentially reduce unnecessary dentin removal and procedural errors while improving the predictability of root canal preparation.

Ultimately, the most appropriate instrumentation system should be selected according to the specific anatomical and clinical requirements of each case. ProTaper Gold, WaveOne Gold, Reciproc Blue, and HyFlex CM should therefore be viewed as complementary technologies rather than competing systems in which one option universally replaces the others. The clinician's understanding of canal anatomy, knowledge of instrument mechanics, appropriate case selection, and controlled instrumentation technique remain at least as important as the specific commercial system selected [1–15].

The future of NiTi instrumentation will therefore likely depend not on the development of a single "ideal" file, but on the integration of improved metallurgy, optimized geometry, intelligent kinematics, advanced imaging, and patient-specific treatment planning. Continued research should focus on determining whether improvements demonstrated in laboratory studies translate into measurable improvements in clinical treatment outcomes, while maintaining the fundamental principles of effective disinfection and maximal preservation.

Conclusions

Contemporary nickel-titanium instrumentation systems have substantially improved the predictability and safety of mechanical root canal preparation. ProTaper Gold, WaveOne Gold, Reciproc Blue, and HyFlex CM are all capable of producing effective canal enlargement while maintaining the original root canal trajectory and limiting excessive dentin removal under appropriate clinical conditions.

The available evidence indicates that no single instrumentation system demonstrates universal superiority across all evaluated parameters. ProTaper Gold provides predictable progressive rotary enlargement and efficient cutting, while WaveOne Gold and Reciproc Blue offer simplified reciprocating

preparation combined with favorable flexibility and resistance to cyclic fatigue. HyFlex CM represents a distinct approach based on controlled-memory metallurgy, providing high flexibility and a reduced tendency to straighten within curved canals.

Differences in the amount of dentin removed between contemporary systems are generally influenced by instrument taper, geometry, preparation sequence, and the initial anatomy of the root canal. Preservation of radicular dentin should therefore remain a fundamental objective of mechanical preparation, with sufficient enlargement achieved to facilitate effective chemical disinfection without unnecessary removal of sound tooth structure.

Similarly, canal transportation and centering ability depend on the interaction between instrument design, alloy characteristics, kinematics, and canal anatomy. Current evidence suggests that both rotary and reciprocating systems can maintain favorable canal centering when appropriately selected and used. The choice between these approaches should therefore be based on the anatomical characteristics of the canal and the clinical objectives rather than on the assumption that one type of kinematics is inherently superior.

Mechanical resistance represents another important consideration. Modern heat-treated and controlled-memory NiTi alloys have substantially improved flexibility and resistance to cyclic fatigue compared with earlier generations of instrumentation. Nevertheless, instrument fracture remains a multifactorial complication influenced by canal curvature, torsional stress, instrument dimensions, repeated use, and operator technique. Improved metallurgical properties reduce mechanical risk but do not eliminate it.

Overall, the most appropriate instrumentation system should be selected according to the individual anatomical and clinical characteristics of each case. Successful root canal preparation depends not only on the technological characteristics of the selected file system but also on appropriate case assessment, preservation of the original canal anatomy, controlled dentin removal, adequate irrigation, and meticulous clinical execution. Future research should prioritize standardized micro-CT and clinical investigations capable of determining whether the differences demonstrated between contemporary NiTi systems translate into meaningful improvements in long-term endodontic treatment outcomes.

The evidence therefore supports a patient- and anatomy-oriented approach to NiTi instrumentation rather than the universal preference for a single commercial system.

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All authors have read and agreed with the published version of the manuscript.

Conflict of Interest Statement: The authors have declared no conflicts of interest.

Declaration of the use of generative AI and AI-assisted technologies in the writing process: In preparing this work, the authors used ChatGPT for the purpose of improving language and readability. After using this tool, the authors have reviewed and edited the content as needed.

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