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ORIGINAL RESEARCH

CORRECTION OF LEDGE FORMATION IN SIMULATED ROOT CANALS USING MANUAL AND ROTARY NICKEL–TITANIUM INSTRUMENTS WITH VARIED KINEMATICS

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Abstract

Background: The aim of this study was to evaluate and compare the effectiveness of manual files and rotary nickel–titanium instruments operating in continuous rotation, reciprocation, and optimum torque reverse (OTR) motion for correction of ledge formation in simulated curved root canals.

Materials and Methods: Eighty standardized acrylic blocks with curved canals were used. Ledges were artificially created at a standardized level. Specimens were randomly divided into four groups (n = 20): manual stainless-steel files, continuous rotary NiTi, reciprocating NiTi, and OTR NiTi systems. Ledge correction was attempted using standardized protocols. Outcomes included success rate of ledge correction, time required to regain working length, and change in canal curvature. The significance level was set at $P \leq 0.05$. Statistical analysis was performed with IBM® SPSS® Statistics Version 25 for Windows.

Results: Manual files demonstrated the highest success rate in bypassing ledges, while reciprocating and OTR systems showed significantly reduced correction time. Continuous rotary instruments exhibited greater change in canal curvature compared with other groups.

Conclusion: Manual files remain the most reliable instruments for initial ledge bypassing, whereas rotary systems particularly those using OTR and reciprocation can efficiently refine canal shaping after correction. Instrument kinematics significantly influence ledge management outcomes.

Keywords: Ledge formation; Acrylic blocks; Rotary instrumentation; Reciprocation; Optimum torque reverse; Canal transportation.

1.INTRODUCTION

Ledge formation is a common procedural error encountered during root canal instrumentation, particularly in curved canals, and is often associated with improper file selection, inadequate glide path establishment, failing to use the instrument in sequential order, inadequate irrigation during shaping, and excessive apical pressure. A ledge may prevent instruments from reaching the full working length, resulting in inadequate cleaning of the apical portion of the canal and potentially compromising the long-term success of endodontic treatment.[1, 2]

Traditionally, manual stainless-steel files, especially when pre-curved, have been advocated for bypassing ledges due to their rigidity and enhanced tactile feedback.[3, 4] However, these instruments are associated with an increased risk of canal transportation and further procedural errors when used improperly in curved canals.[5, 6] The introduction of nickel–titanium (NiTi) rotary instruments has significantly improved the efficiency and safety of root canal preparation owing to their superior flexibility and shape memory.[7, 8] Contemporary rotary systems operate using different kinematics, including continuous forward rotation, reciprocation, and optimum torque reverse (OTR) motion. Continuous rotation allows efficient dentin

removal but may increase torsional stress, while reciprocating motion has been shown to reduce cyclic fatigue and instrument separation.[9, 10] OTR motion represents a hybrid kinematic approach that alternates between clockwise and counterclockwise rotation in response to torque load, potentially enhancing canal centering and instrument safety.[11, 12] Despite advances in instrumentation systems, limited data are available regarding the effectiveness of these different kinematics in correcting ledge formation once it has occurred.[13, 14] Therefore, the present study aimed to compare manual files and rotary NiTi instruments operating in continuous rotation, reciprocation, and OTR motion for the correction of ledge formation in simulated curved root canals with artificial ledges. [9, 10]

2. MATERIALS AND METHODS

2.1 Study Design

This experimental in vitro study compared four instrumentation techniques for the correction of artificial ledge formation using standardized simulated root canals in acrylic resin blocks.[9, 14]

2.2 Sample Size Determination

Sample size was calculated a priori based on previous studies on ledge correction and canal shaping. Assuming a medium-to-large effect size (f = 0.40), α = 0.05, and 80% power, 18 specimens per group were required. To ensure robustness and account for potential specimen loss, 20 specimens were included per group, resulting in a total of 80 root canal blocks, sufficient to detect significant differences across all parameters

2.3 Sample Selection

Eighty transparent acrylic resin blocks (Endo Training Blocks; Dentsply Sirona) were used. All blocks had standardized canal characteristics, including a curvature of 30° a curvature radius of 5 mm, canal length of 16 mm and apical diameter 0.15 mm. Figure (1)

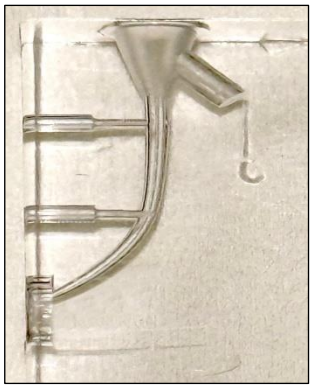

Figure 1. Simulated canal before ledge formation under x8 magnification

2.4 Artificial Ledge Creation

Artificial ledges were created at the beginning of the canal curvature by advancing size #35 and #40 stainless-steel K-files with excessive apical pressure and without respecting the canal curvature.[15, 16] Figure (2)

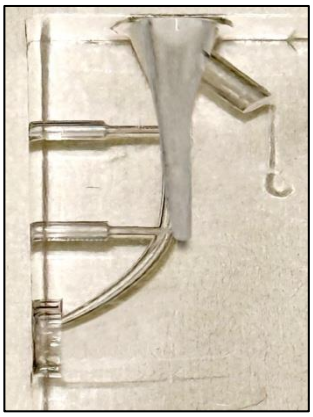

Figure 2. Simulated canal after ledge formation under x8 magnification

Ledge formation was confirmed when a #10 K-file could no longer reach the original working length. This method replicates clinical ledge formation in curved canals.[6,17]

2.5 Ledge Correction Protocol

All procedures were performed by a single experienced operator under dental operating microscope (DOM) Zumax OMS2350 (Zumax Medical Co., Ltd., Suzhoi, China) ×8 magnification to minimize variability.[14] Throughout instrumentation, canals were irrigated with distilled water to remove debris and prevent heat-related resin distortion. No chemical irrigants were used.[9] Prior to ledge correction, patency up to the ledge level was verified using a #10 K-file.

2.5.1 Group Allocation

Specimens were randomly assigned into four groups (n = 20 each):

Group I – Manual Instrumentation:

In this group after bypassing the ledge using precurved K-files (#08–#15), files #20, and #25 were pre-curved at the apical 2–3 mm and introduced using gentle watch-winding and short push–pull motions with minimal apical pressure.[3, 4] Once the #10 K-file reached the original WL, enlargement was cautiously completed up to size #30 and step back instrumentation upto #45.

In all rotary groups, ledge correction was initiated only after patency beyond the ledge was regained with a #10 K-file after bypassing was done as in group I.[9, 10] Instrumentation was performed using gentle 2–3 mm pecking motions with minimal apical pressure. After each insertion, instruments were withdrawn, cleaned, and the canal irrigated. Patency was reconfirmed after each cycle using a #10 K-file.[11, 18] All rotary groups were operated using Wismy Endo Motor (Black Edition; Bomedent, Changzhou, China).

Group II – Continuous Rotary Motion :
After coronal flaring Protaper next file (PTN) X2 (25/.06) was operated at a speed of 300 rpm and 2.5 Ncm of torque, according to the manufacturer's instructions.

Group III – Reciprocating Motion:
After coronal flaring WaveOne Gold: WOG Primary (25/.07) variable taper was operated at a speed of 300 rpm and 2.5 Ncm of torque (30° clockwise and 150° counterclockwise) , according to the manufacturer's instructions.

Group IV –(OTR) Motion:
After coronal flaring Protaper next file (PTN) X2 (25/.06) was operated using at a speed of 300 rpm and 2.5 Ncm of torque, according to the manufacturer's instructions.

Each instrument was used according to manufacturer guidelines and discarded to avoid fatigue-related bias.

A maximum time of 5 minutes was allowed for ledge correction per specimen. Failure to regain the original WL within this time was recorded as unsuccessful.[15, 17]

2.6 Evaluation Parameters

2.6.1 Success of Ledge Correction

Defined as the ability to regain the original working length with a #10 K-file without resistance. Outcomes were recorded as successful or unsuccessful.[4, 14]

2.6.2 Change in Canal Curvature (Schneider's Method)

Change in canal curvature was evaluated before and after ledge correction using Schneider's method.[19] in combination with digital image analysis. Standardized digital images of each acrylic resin block were obtained before and after instrumentation using Zumax OMS2350 (Zumax Medical Co., Ltd., Suzhoi, China) DOM equipped with a digital camera at a fixed magnification of ×8. During image acquisition, each specimen was positioned on a flat, stable white surface and aligned parallel to the microscope optical axis to ensure consistent orientation, magnification, and illumination for all images. The captured images were imported into AutoCAD software (Autodesk Inc., USA) and calibrated using the known reference dimension of the resin block to ensure measurement accuracy. Canal curvature was measured according to Schneider's method as follows; a straight reference line was drawn parallel to the long axis of the canal from the canal orifice to the point where the canal began to deviate (A); a second line was drawn from this point of deviation to the apical foramen (B). The angle formed between the two lines represented the degree of canal curvature (α). Figure (3)

Curvature angles were recorded before instrumentation and after ledge correction. The percentage change in canal curvature was calculated using the following formula:

$$\text{Curvature Change (\%)} = \frac{\text{pre-instrumentation angle} - \text{post-instrumentation angle}}{\text{pre-instrumentation angle}} \times 100$$

Higher percentage values indicated greater canal straightening, whereas lower values reflected better preservation of the original canal curvature. [8, 20]

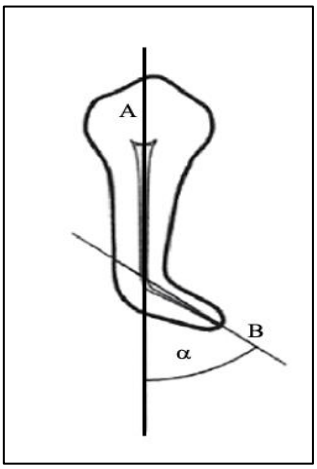

Figure 3. Angle of curvature by Schneider

2.6.3 Time Required for Ledge Correction

Measured in seconds using a digital stopwatch, starting from initial file insertion until the #10 K-file smoothly reached the original WL. [10, 18]

2.7 Statistical Analysis

Normality of the data was assessed using the Kolmogorov–Smirnov and Shapiro–Wilk tests. Parametric variables were analyzed using one-way or two-way ANOVA, while non-parametric success rate data were evaluated with the Chi-square test. Statistical significance was set at $P \leq 0.05$. All analyses were performed using IBM® SPSS® Statistics Version 25 for Windows.

3. RESULTS

A significant difference was observed among the four instrumentation groups for ledge correction success ($p = 0.041$). Manual and reciprocating instrumentation achieved the highest success rates, continuous rotation showed intermediate performance, and OTR motion had the lowest success. No significant difference was found between manual and reciprocating groups ($p > 0.05$), whereas OTR differed significantly from both ($p < 0.05$) (Table 1).

Table 1. The frequencies of Success Rate of Ledge Correction of different groups.

Variables	Success Rate of Ledge Correction		
	Total canals	n	Success rate %
Manual	20	19	95%
Continuous Rotation (PTN)	20	17	85%
OTR (PTN)	20	16	80%
Reciprocation (WOG)	20	19	95%
p-value	**0.041***		

*; significant (p<0.05)

Table 2. The mean and SD of change in canal curvature of different groups.

Variables	Change in canal curvature	
	Mean	SD
Manual	2	0.7
Continuous Rotation (PTN)	5.6	1.3
OTR (PTN)	3.8	1
Reciprocation (WOG)	3.1	0.9
p-value	**<0.001***	

*; significant (p<0.05)

Table 3. The mean and SD of Time Required for Ledge Correction of different groups.

Variables	Time Required for Ledge Correction	
	Mean	SD
Manual	182	36
Continuous Rotation (PTN)	96	22
OTR (PTN)	108	25
Reciprocation (WOG)	88	20
p-value	**<0.001***	

*; significant (p<0.05)

4. DISCUSSION

Ledge formation represents a challenging procedural error that compromises canal negotiation, working length control, and treatment outcome.[6,15] The present study evaluated manual stainless-steel instrumentation and rotary nickel–titanium systems operating under continuous rotation, reciprocation, and optimum torque reverse (OTR) motion for ledge correction in standardized simulated root canals.[7, 10] The findings demonstrate that instrument kinematics significantly influence ledge correction success, curvature preservation, and procedural efficiency, often outweighing similarities in instrument design and taper.[13, 20]

Acrylic blocks were used to provide a standardized and reproducible experimental model, eliminating anatomical variability inherent in extracted teeth and allowing precise evaluation of canal transportation and curvature changes.[1,14] Manual stainless-steel K-files were included as a reference technique, as they represent the traditional and widely accepted method for negotiating and bypassing ledges due to their superior tactile feedback, pre-curving capability, and controlled hand movements.[3,4]

The inclusion of continuous rotation, reciprocation, and optimum torque reverse (OTR) motion allowed a comprehensive assessment of how different rotary behaviors influence ledge correction efficiency and canal preservation. By integrating manual instrumentation and three distinct rotary kinematics, the present protocol enabled a precise evaluation of how tactile control versus engine-driven motion dynamics influence ledge correction success, curvature preservation, and procedural efficiency.

Glide path confirmation using **a** #10 K-file was performed in all specimens prior to further instrumentation to establish a reproducible and safe pathway beyond the ledge. This step reflects standard clinical practice and ensured that subsequent manual or rotary instruments were guided along the original canal trajectory, minimizing the risk of secondary procedural errors such as ledge deepening or canal transportation.[9]

WaveOne Gold and ProTaper Next were chosen because they represent different kinematic approaches; WaveOne Gold is reciprocating, ProTaper Next is continuous rotation, and it can also be used in OTR motion.[21] WaveOne Gold has a parallelogram/offset cross-section, whereas ProTaper Next has a rectangular off-centered cross-section.[7, 10] This influences cutting efficiency, debris removal, and canal centering ability. Both systems include instruments with similar apical sizes and variable taper, allowing a fair comparison and reducing the confounding effect of instrument dimensions while focusing on kinematics and design.[2] Both instruments are made from heat-treated NiTi alloys, which improve flexibility and cyclic fatigue resistance compared to conventional NiTi.[3,7] This makes them suitable for shaping curved canals and for safe ledge bypassing experiments.

Manual instrumentation and reciprocating rotary motion demonstrated the highest ledge bypass success rates (95%), whereas OTR motion showed the lowest success among rotary systems, followed by continuous rotation. The high success of manual files is attributed to their pre-curving capability, superior tactile feedback, and controlled watch-winding movements, which allow precise redirection of the file toward the original canal path.[3,4]

Reciprocating instrumentation matched manual success despite being engine-driven. This can be explained by its alternating clockwise and counterclockwise motion, which limits continuous engagement at the ledge site, reduces the screw-in effect, and promotes frequent disengagement and re-centering of the instrument.[7, 18] In contrast, continuous rotation allows uninterrupted cutting at the ledge, increasing the risk of deviation and reducing bypass success.[20] OTR motion, although safer than continuous rotation, remains predominantly forward-rotating, and torque reversal may occur too late to prevent dentin removal at the ledge, explaining its reduced success rate.[11]

Preservation of the original canal curvature is a critical objective during ledge correction, as excessive straightening may compromise apical anatomy, increase the risk of further procedural errors, and negatively affect long-term treatment outcomes.[13, 14] In the present study, significant differences were observed among the tested instrumentation techniques with respect to the degree of canal curvature alteration following ledge correction, underscoring the influence of instrument kinematics and mode of operation on shaping behavior.[7,8] Manual stainless-steel instrumentation resulted in the lowest percentage change in canal curvature, indicating superior preservation of the original canal anatomy.[3,4] This finding can be attributed to the ability to pre-curve manual files and to the enhanced tactile feedback they provide, allowing the operator to carefully redirect the file along the original canal path. The use of controlled watch-winding and short push–pull motions enables incremental negotiation of the ledge while minimizing uncontrolled dentin removal along the outer curvature, particularly important in curved canals.[6]

Continuous rotary instrumentation demonstrated the greatest degree of canal straightening among all groups,

consistent with the tendency of nickel–titanium instruments operating in uninterrupted clockwise rotation to return to their straight configuration under load.[7] Sustained rotational motion generates continuous lateral forces against the canal walls at the point of maximum curvature, promoting progressive straightening. During ledge correction, repeated engagement at the ledge site can exacerbate this effect. [9]

Reciprocating motion showed significantly lower curvature change compared with continuous rotation and OTR motion, indicating better preservation of canal anatomy.[9,10] The alternating clockwise and counterclockwise movements characteristic of reciprocation limit continuous dentin engagement and reduce sustained lateral pressure on the canal walls. This repeated disengagement allows the instrument to re-center within the canal and follow the existing curvature more closely, even during the challenging process of ledge correction.[20] Despite being engine-driven, reciprocating instruments were able to maintain canal curvature at levels comparable to manual instrumentation, highlighting the effectiveness of this kinematic approach.[11]

OTR motion produced intermediate curvature changes, preserving canal anatomy better than continuous rotation but less effectively than reciprocation. Although OTR systems are designed to reduce torsional stress by reversing rotation upon reaching preset torque limits, forward rotation remains the dominant motion. As a result, dentin removal along the outer curvature may occur before torque reversal is triggered, leading to measurable canal straightening.[20]

The use of standardized digital imaging under a dental operating microscope at ×5 magnification and precise angle measurement using AutoCAD software enhanced the accuracy and reproducibility of curvature assessment in this study.[14] This methodological approach allowed objective quantification of subtle changes in canal geometry and reinforced the reliability of the observed differences among instrumentation techniques. Importantly, these findings indicate that kinematic behavior plays a more decisive role in curvature preservation during ledge correction than instrument design or taper alone.[8]

Rotary instrumentation significantly reduced the time required for ledge correction compared with manual files. Reciprocation was the fastest technique, followed by continuous rotation and OTR motion. Manual instrumentation, although effective, required the longest time due to the need for gradual tactile negotiation.

5. CONCLUSION

Within the limitations of this study, manual instrumentation and reciprocating rotary motion achieved the highest success in ledge correction, with reciprocation requiring the least time while preserving canal anatomy. Continuous rotation caused the greatest curvature straightening, increasing the risk of procedural errors, while OTR motion reduced deviation compared with continuous rotation but was less effective than reciprocation. These findings highlight that instrument kinematics, rather than geometry alone, primarily determine performance during ledge management.

DECLARATION

Conflict of interest:
Authors declare that there is no conflict of interest
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Author Contribution:
All authors have contributed substantially to the manuscript and all have reviewed the final manuscript

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