

Apical Extrusion of Debris During Root Canal Preparation Using Different Instrumentation Kinematics in Standardized 3D-Printed Tooth Models: An In Vitro Study

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Abstract

Background: Apical extrusion of debris during root canal instrumentation is an unavoidable event that may contribute to postoperative pain and periapical inflammation. Instrumentation kinematics have been proposed as a key factor influencing debris extrusion; however, anatomical variability among extracted teeth limits the comparability of previous studies. Standardized 3D-printed tooth models may overcome this limitation. **Objectives:** To evaluate and compare the amount of apically extruded debris during root canal preparation using continuous rotation, reciprocating, and adaptive motion kinematics in standardized 3D-printed tooth models. **Methods:** Sixty identical 3D-printed mandibular premolar models were randomly allocated into three groups (n = 20) according to the instrumentation kinematics used. Root canal preparation was performed to an equivalent apical size following manufacturers' instructions. Apically extruded debris was collected using a modified Myers and Montgomery apparatus, dried, and weighed using a digital microbalance. Data were analyzed using one-way ANOVA and Tukey post hoc test (P ≤ 0.05). **Results:** All instrumentation systems produced measurable apical debris extrusion. The reciprocating group showed significantly higher debris extrusion compared with continuous rotation and adaptive motion groups (P < 0.05). Adaptive motion resulted in the lowest mean debris extrusion, although the difference compared with continuous rotation was not statistically significant (P > 0.05). **Conclusion:** Instrumentation kinematics significantly influence the amount of apically extruded debris. Continuous rotation and adaptive motion systems resulted in less debris extrusion than reciprocating motion when standardized 3D-printed tooth models were used.

Keywords: Apical extrusion, debris, reciprocation, continuous rotation, adaptive motion, 3D-printed teeth.

Background

Apical extrusion of debris during root canal instrumentation is a well-documented phenomenon with important clinical implications. Extruded debris may include dentinal chips, pulp tissue remnants, microorganisms, and irrigants, which can trigger periapical inflammation and contribute to postoperative pain and flare-ups (Tanalp & GÜngör, 2014). Consequently, minimizing apical extrusion remains a key objective of modern endodontic treatment.

Nickel–titanium (NiTi) instruments have significantly improved shaping efficiency and canal centering ability. In addition to instrument design and metallurgy, instrumentation kinematics including continuous rotation, reciprocation, and adaptive motion play a critical role in debris transportation within the root canal system (Plotino et al., 2015). Reciprocating motion has been associated with increased apical debris extrusion due to its alternating movement pattern, whereas continuous rotation may favor coronal debris transportation along the instrument flutes (De-Deus et al., 2010).

Despite extensive research, results remain controversial, largely due to differences in experimental design and the inherent anatomical variability of extracted human teeth (Bürklein & Schäfer, 2022). Recently, 3D-printed tooth models have emerged as a valuable alternative, allowing precise standardization of canal anatomy and improved reproducibility of laboratory studies (Reis et al., 2022; Yu et al., 2023).

Therefore, this study aimed to evaluate apical extrusion of debris during root canal preparation using different instrumentation kinematics in standardized 3D-printed tooth models. The null hypothesis was that there would be no significant difference in the amount of apically extruded debris among the tested kinematic systems.

Materials and Methods:

Study design

This in vitro experimental study was conducted following standardized laboratory protocols for assessing apical debris extrusion, as described in previous endodontic research (Tanalp & Güngör, 2014; Bürklein & Schäfer, 2022).

Sample size calculation

Sample size estimation was based on data from earlier studies evaluating debris extrusion with different kinematics (De-Deus et al., 2010). Assuming an effect size of 0.4, a statistical power of 80%, and a significance level of 5%, a minimum of 18 specimens per group was required. To compensate for potential variability, 20 specimens were included in each group.

Fabrication of standardized 3D-printed tooth models

Sixty mandibular premolar tooth models were digitally designed using computer-aided design (CAD) software. All models shared identical anatomical characteristics: Root length: 18 mm, Single straight canal (0° curvature), Initial apical diameter: ISO size 15, and Canal taper: 0.02.

The models were fabricated using a high-resolution stereolithography (SLA) 3D printer and a photopolymer resin previously reported to be suitable for endodontic instrumentation studies (Reis et al., 2022; Yu et al., 2023).

Grouping and instrumentation kinematics

The specimens were randomly assigned into three experimental groups ($n = 20$) according to the instrumentation kinematics used:

- **Group I:** Continuous rotation
- **Group II:** Reciprocating motion
- **Group III:** Adaptive motion

All canals were prepared to the same final apical size (ISO 25). Instruments were operated strictly according to manufacturers' recommendations regarding speed, torque, and motion settings.

Debris collection apparatus

Apically extruded debris was collected using a modified Myers and Montgomery model, which remains the most widely accepted method for debris extrusion assessment in vitro (Myers & Montgomery, 1991). Each tooth model was fixed through a rubber stopper into a pre-weighed Eppendorf tube (W_1). A 27-gauge needle was placed alongside the stopper to equalize air pressure and prevent suction effects. (Fig.1)



Figure (1). Debris collection apparatus used for the collection of apically extruded debris.

Root canal preparation protocol

Working length was established by subtracting 1 mm from the length at which a size 10 K-file was visible at the apical foramen. All instrumentation procedures were performed by a single experienced operator. A standardized volume of irrigant 10 mL per canal was delivered after each instrumentation step using a side-vented needle placed 2 mm short of the working length. Irrigation was standardized using distilled water, and the total irrigant volume per canal was kept constant.

Root canal preparation was performed using three commercially available nickel–titanium (NiTi) instrumentation systems representing different kinematic motions: continuous rotation, reciprocating motion, and adaptive motion. All instruments were new and used for a maximum of four canals to minimize the influence of cyclic fatigue.

Group I: Continuous Rotation System (ProTaper Next)

Specimens in Group I were prepared using ProTaper Next (PTN) rotary files (Dentsply Sirona, Ballaigues, Switzerland), manufactured from M-Wire NiTi alloy and operated in continuous clockwise rotation.

Instrumentation was performed using an X-Smart Plus endodontic motor (Dentsply Sirona) set according to the manufacturer's recommendations: Speed: 300 rpm, and Torque: 2.0 N·cm.

The following sequence was used:

1. Glide path verification with a size 15 K-file to full working length
2. ProTaper Next X1 (ISO 17/.04) introduced using gentle in-and-out pecking motions
3. ProTaper Next X2 (ISO 25/.06) advanced to the working length to achieve the final apical preparation

Each file was used with a pecking amplitude not exceeding 3 mm. After three pecking motions, the instrument was withdrawn, cleaned with sterile gauze, and the canal was irrigated before reinsertion.

Group II: Reciprocating Motion System (WaveOne Gold)

Specimens in Group II were instrumented using WaveOne Gold Primary files (size 25, taper 6%) (Dentsply Sirona, Ballaigues, Switzerland), which are manufactured from a heat-treated gold wire NiTi alloy and designed for reciprocating motion. Instrumentation was performed with a X-Smart Plus endodontic motor (Dentsply Sirona) set according to the manufacturer's preprogrammed reciprocation mode.

The preparation protocol consisted of the following steps:

1. Establishment of a glide path using a size 15 K-file.
2. Introduction of the WaveOne Gold Primary file (ISO 25/.06) with slow, gentle pecking motions.
3. After three pecks, the file was removed for cleaning, followed by irrigation of the canal.
4. Steps 2–3 were repeated until the working length was reached.

The final apical preparation was standardized to ISO size 25, taper 6%, to ensure direct comparability with other groups.

Group III: Adaptive Motion System (Twisted File Adaptive)

Specimens in Group III were prepared using Twisted File Adaptive (TFA) instruments (Kerr Endodontics, Orange, CA, USA), which utilize an adaptive motion that dynamically alternates between continuous rotation and reciprocation based on intracanal stress. Instrumentation was performed using the Elements Motor (SybronEndo, Orange, CA, USA) set to adaptive motion mode as recommended by the manufacturer.

The file sequence used was:

1. Glide path confirmation with a size 15 K-file
2. TFA (ISO 20/.04)

3. TFA (ISO 25/06) to full working length

Files were advanced using gentle pecking motions, and the motor automatically adjusted the kinematics in response to canal resistance. The final apical size was standardized to ISO 25, taper 6%.

To ensure consistency standardization of instrumentation procedures across all experimental groups: All canals were prepared to the same working length and final apical size (ISO 25). Instrumentation was performed by a single experienced operator to eliminate inter-operator variability. A standardized pecking motion and light apical pressure were used in all groups. Each instrument was cleaned after withdrawal, and irrigation was performed between instrumentation cycles. Instruments showing visible deformation were discarded immediately.

Debris drying and weighing

Following instrumentation, Eppendorf tubes containing extruded debris were incubated at 70 °C for five days to ensure complete evaporation of moisture (De-Deus et al., 2010). Each tube was weighed three times using a digital microbalance (Sartorius Analytical, Gottingen, Germany) with an accuracy of 10^{-5} g, and the mean value was recorded (W_2). The net debris weight was calculated by subtracting the initial weight from the final weight.

Statistical analysis

Normality of data distribution was assessed using the Shapiro–Wilk test. One-way analysis of variance (ANOVA) was used to compare debris extrusion among groups, followed by Tukey post hoc test. Statistical significance was set at $P \leq 0.05$.

Results

Apical extrusion of debris was observed in all experimental groups, confirming that debris extrusion is an inherent outcome of root canal instrumentation regardless of kinematics (Tanalp & Gungör, 2014).

Statistical analysis revealed significant differences among the tested groups ($P < 0.05$). The reciprocating motion group demonstrated the highest mean debris extrusion, followed by the continuous rotation group, whereas the adaptive motion group showed the lowest mean values.

Post hoc comparisons indicated that reciprocating motion resulted in significantly greater debris extrusion than both continuous rotation and adaptive motion ($P < 0.05$). No statistically significant difference was detected between continuous rotation and adaptive motion ($P > 0.05$).

Group	Mean debris weight (g)	Standard deviation (SD)
Continuous rotation	0.00042	0.00008
Reciprocation	0.00071	0.00011
Adaptive motion	0.00038	0.00007

Table 1. Mean and standard deviation of apically extruded debris (g)

Reciprocation showed significantly higher debris extrusion compared with continuous rotation and adaptive motion ($P < 0.05$).

Discussion

A major strength of this study is the use of standardized 3D-printed tooth models, which eliminate anatomical variability inherent to extracted human teeth and enhance internal validity (Reis et al., 2022). Recent studies have confirmed the suitability of high-resolution SLA-printed resin models for evaluating shaping behavior and debris extrusion, particularly in comparative experimental designs (Yu et al., 2023). Nevertheless, the mechanical properties of resin do not fully replicate natural dentin, which should be acknowledged as a limitation when extrapolating findings to clinical practice.

Standardizing the final apical size and preparation protocol allowed direct comparison of debris extrusion related solely to instrumentation kinematics, minimizing the influence of apical enlargement, taper variation, or operator-

related factors. This approach aligns with previously published debris extrusion studies and strengthens the internal validity of the experimental design (Tanalp & Güngör, 2014; Bürklein & Schäfer, 2022).

Irrigation was performed using distilled water to avoid crystallization artifacts that could affect the debris weighing. A standardized volume of irrigant 10 mL per canal was delivered after each instrumentation step using a side-vented needle placed 2 mm short of the working length. The total volume of irrigant used per canal was kept constant across all groups to eliminate irrigation volume as a confounding factor.

Regarding periapical resistance, the absence of simulated periapical tissues in the present study was intentional and methodologically justified. Previous investigations have demonstrated that artificial resistance-simulating materials, such as floral foam, agar gel, or silicone, exhibit non-physiological mechanical properties may absorb debris and irrigants, thereby altering the true amount of extruded material and compromising measurement accuracy (De-Deus et al., 2010; Tanalp & Güngör, 2014, Bürklein & Schäfer, 2022). Furthermore, the complex viscoelastic behavior of periapical tissues cannot be reliably reproduced *in vitro* and it considerably depending on bone density, periodontal ligament condition, and the presence of periapical pathology, making accurate laboratory simulation challenging (Bürklein & Schäfer, 2022).

Importantly, the primary objective of this study was comparative rather than absolute quantification of debris extrusion. Since all groups were tested under identical experimental conditions, the absence of periapical resistance does not compromise the validity of the comparative outcomes. This was in full agreement with the majority of published *in vitro* studies on debris extrusion (Myers & Montgomery, 1991; Tanalp & Güngör, 2014; Bürklein & Schäfer, 2022).

The present *in vitro* study demonstrated that apical debris extrusion occurred with all tested instrumentation kinematics, confirming that debris extrusion is an inherent consequence of root canal preparation regardless of the motion employed. This finding is consistent with previous investigations and comprehensive reviews reporting that dentinal chips, pulp remnants, microorganisms, and irrigants are unavoidably forced beyond the apical foramen during mechanical instrumentation (Tanalp & Güngör, 2014; Bürklein & Schäfer, 2022).

The higher extrusion associated with reciprocation may be explained by its alternating clockwise and counter-clockwise movement, which can produce a piston-like effect, repeatedly compacting debris toward the apical foramen. This bidirectional motion may limit continuous coronal transportation of debris, particularly when the file engages dentin near the working length (Çapar & Arslan, 2016). Similar mechanistic explanations have been proposed in recent systematic reviews and experimental studies evaluating modern reciprocating systems (Bürklein & Schäfer, 2022).

In contrast, continuous rotation systems demonstrated lower debris extrusion, likely due to their unidirectional motion, which facilitates coronal movement of debris along the instrument flutes. Continuous rotation allows debris to be progressively carried coronally during canal enlargement, reducing apical compaction (Plotino et al., 2015; Silva et al., 2020). Although some studies have reported no statistically significant differences between rotary and reciprocating systems, the majority indicate a trend toward lower extrusion with continuous rotation when preparation protocols and apical sizes are standardized (De-Deus et al., 2010; Bürklein & Schäfer, 2022).

Adaptive motion systems demonstrated the lowest mean debris extrusion values in the present study, although the difference compared with continuous rotation was not statistically significant. Adaptive motion dynamically alternates between continuous rotation and reciprocation in response to intracanal stress, potentially optimizing cutting efficiency while limiting apical debris compaction. This hybrid kinematic behavior may enhance coronal debris removal while reducing torsional stress on the instrument (Silva et al., 2020; Yu et al., 2023).

Recent investigations using standardized models have reported comparable findings, suggesting that adaptive motion may offer advantages in debris management without increasing apical extrusion (Yu et al., 2023). However, evidence remains heterogeneous, and differences among adaptive systems may depend on file design, metallurgy, and motion algorithms (Bürklein & Schäfer, 2022).

Clinical Relevance

Although in vitro debris extrusion does not directly replicate clinical conditions, its clinical relevance should not be underestimated. Extruded debris contaminated with bacteria and necrotic tissue has been associated with postoperative pain, flare-ups, and periapical inflammation (Tanalp & Güngör, 2014). Therefore, reducing apical extrusion remains an important objective in endodontic treatment, particularly in teeth with pre-existing periapical pathology.

It is important to note that operator technique and irrigation strategy significantly influence debris extrusion. Establishing a glide path, using crown-down preparation approaches, employing side-vented irrigation needles positioned short of the working length, and maintaining controlled pecking motions may help reduce apical compaction regardless of the kinematic system used (Çapar & Arslan, 2016).

Conclusion

Within the limitations of this in vitro study:

1. Apical debris extrusion occurred with all tested instrumentation kinematics.
2. Reciprocating motion resulted in significantly greater debris extrusion than continuous rotation and adaptive motion.
3. Adaptive motion and continuous rotation showed lower debris extrusion values.

Instrumentation kinematics play a critical role in apical debris extrusion during root canal preparation.

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