ORIGINAL ARTICLE

Turk Endod J 2025;10(3):171–176
doi: 10.14744/TEJ.2025.08860

The effect of different irrigation activation procedures on the penetration of a contrast irrigation solution into lateral canals of 3D-printed tooth models

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Purpose: The aim of this study was to compare the effectiveness of the XP-Endo Finisher R (XPFR), sonic irrigation (EDDY) and manual dynamic activation (MDA) in enhancing the penetration of a contrast irrigation solution into the lateral canals of 3D printed teeth.

Methods: A total of 45 3D-printed teeth with lateral canals 3 mm from the root apex were used in this study. Root canals were prepared up to size #35.06. The specimens were then divided into three groups (n=15) according to the irrigation activation technique used: XPFR, EDDY and MDA. Each technique was applied using 1.5 mL of 1% methylene blue (MB) as the contrast dye. Penetration depth was assessed via images captured under a dental microscope, and scored on a four-point scale. Data analysis was performed using Kruskal-Wallis and Mann-Whitney U tests, with statistical significance set at $p<0.05$.

Results: Statistical analysis revealed significant differences among the groups (p=0.002). In the XPFR group, penetration of MB into the lateral canals was lower than in the EDDY (p=0.002) and MDA (p=0.008) groups.

Conclusion: EDDY and MDA techniques were more effective than XPFR in facilitating MB penetration into lateral canals of 3D-printed models.

Keywords: 3D-printed teeth; irrigant penetration; manual dynamic activation; sonic irrigation; XP-Endo Finisher R.

Introduction

The root canal system has a complex anatomy, especially in the apical third (1). This is because anatomical variations such as isthmuses, lateral and accessory canals and apical deltas are more common in this region (2). These anatomical complexities make it more difficult to clean the apical third of the root canal system. De Deus has reported that lateral canals tend to be concentrated in the apical region, making them particularly difficult to reach with standard irrigation protocols. Their narrow diameter and variable positioning limit access, thereby complicating the thorough removal of tissue debris and microbial contaminants (3).

In an effort to improve irrigant delivery into anatomically complex regions of the root canal system, several activation techniques have been introduced. These approaches

Cite this article as: Uslu M, Dayican NM, Turker SAB. The effect of different irrigation activation procedures on the penetration of a contrast irrigation solution into lateral canals of 3d-printed tooth models. Turk Endod J 2025;10:171-176.
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Submitted: April 14, 2025 Revised: June 13, 2025 Accepted: June 20, 2025 Published: December 09, 2025

are designed to increase the depth of irrigant penetration and enhance the removal of residual debris and microorganisms (4). Techniques such as manual dynamic activation (MDA), sonic agitation (e.g., EDDY), and mechanical agitation using devices like the XP-Endo Finisher R have received growing attention for their potential to optimize irrigant efficacy in inaccessible areas. Manual dynamic activation (MDA) entails the use of a well-adapted gutta-percha cone, which is manually agitated within the canal in a push-pull motion to improve irrigant flow. This technique has been associated with enhanced smear layer removal in multiple studies (5-7). The XP-Endo Finisher R (XPFR) (FKG, La Chaux-de-Fonds, Switzerland) is a specialized instrument designed to enhance the removal of root canal filling materials, particularly in curved or oval-shaped canals, following conventional retreatment procedures. The MaxWire (Martensite Austenite Electropolish Flex, FKG, Dentaire) technology is used in this file system. XPFR improves the distribution of the irrigation solutions. According to the manufacturer, the XPFR is able to abrade the dentine walls and access irregular areas while maintaining the original anatomy of the root canals. It can be used as an adjunct to the final step with any file system with a diameter of #30 or larger (5). It has also been used as a complementary approach to irrigation procedures in teeth with complex anatomy, such as oval root canals. (6). One of the sonic irrigation activation systems, EDDY (VDW, Munich, Germany), consists of a flexible polyamide tip (size #25.04). It is connected to an air scaler operating at 6 kHz. This system produces vigorous fluid agitation and has demonstrated efficacy in lowering bacterial counts (7), promoting tissue dissolution more effectively than passive ultrasonic irrigation (PUI) (8), and improving debris removal from root canals (9).

3D-printing is well established in dentistry and recently has been integrated into modern endodontics. It has been utilized to create various models for both educational and research purposes, such as comparing the different rotary instruments (10), obturation techniques (11) and various irrigation methods (12). Currently, various 3D printing technologies based on distinct principles, including Selective Laser Melting (SLM), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Stereolithography (SLA), Digital Light Processing (DLP), have been extensively studied and implemented in the field of dentistry. SLA printing is particularly advantageous in creating dental models, Among the commonly employed materials in dental 3D printing, photopolymer resins stand out due to their ability to undergo precise photopolymerization when exposed to specific wavelengths of light. These resins are primarily utilized in SLA printers, a technology that enables the fabrication of high-resolution, intricate models with excellent dimensional accuracy (13).

A review of the existing literature reveals a lack of studies directly comparing the influence of XPFR, EDDY and MDA techniques on the depth of irrigation solution penetration into lateral canals. The in vitro study was designed to evaluate and compare the penetration efficiency of a contrast dye into the lateral canals of standardized 3D printed root canal models of three applied activation methods. The study was conducted under the null hypothesis that no statistically significant differences would exist in penetration depth among the evaluated techniques.

Materials and Methods

A total of 45 transparent and radiopaque 3D-printed maxillary lateral incisor models were fabricated by a commercial provider (Ancorax Software and Medical Devices, Ankara, Türkiye). The sample size of the study was calculated with reference to the study conducted by Gregorio et al. (14), Spoorthy et al. (15) and Andrade-Junior et al. (16). All root canals were standardized to a length of 22 mm, with a 0.06 taper and an apical diameter of 0.30 mm. Each model included a lateral canal 3 mm in length and 0.15 mm in diameter, positioned 3 mm coronally from the apical terminus of the main canal (Fig. 1).

Prior to the experimental procedure, the teeth were embedded in polyvinyl siloxane impression material (Hydrise Light, Zhermack, Italy) to mimic periodontal support and clinical conditions.

Root Canal Preparation

The working length was established as 1 mm short of the full canal length. The root canal instrumentation was shaped with EndoArt Touch Gold (Inci Dental Productions Co, İstanbul, Türkiye) rotary files up to size #35/0.06 in accordance with the manufacturer's recommended protocol. During the shaping procedures, canals were irrigated with distilled water. After completion of the instrumentation, the patency of the main and lateral root canals was confirmed with a #10 K-file.

The teeth were allocated into three groups based on the irrigation activation technique employed (n=15). A 1% methylene blue solution (Sigma-Aldrich, Steinheim, Germany) was used as a contrast irrigating solution (CIS) to assess the depth of penetration, in accordance with a previously published study (17). The root canals were filled with the 1% methylene blue solution and subsequently subjected to activation using three different methods: XPFR, EDDY, and MDA.

- Group XPFR: The 1% methylene blue applied to the ca-

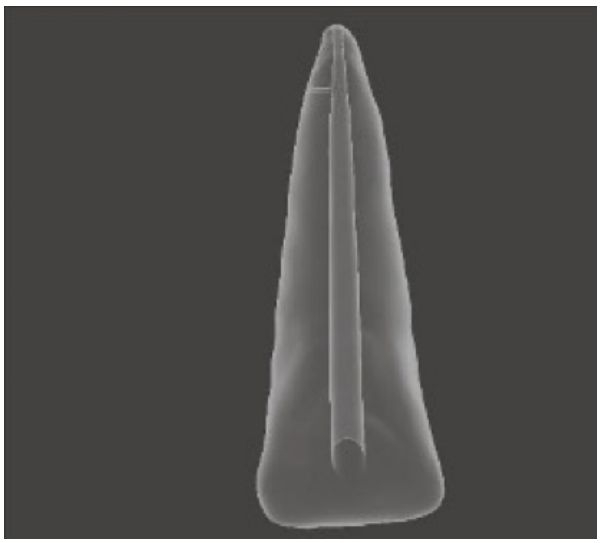

Fig. 1. Construction of transparent 3D printed dental models using digital design technologie.

nals was activated with an XPFR file with a torque of 1 N-cm at 800 rpm along the WL. XPFR was applied in 7-8 mm up and down movements according to the manufacturer's instructions.

- Group EDDY: A size 25/.04 EDDY polyamide tip was inserted 2 mm short of the working length and connected to a TA-200 air scaler (Micron, Tokyo, Japan). Sonic activation was applied for 60 seconds at a frequency of 6 kHz.
- Group MDA: A 35/.06 gutta-percha (Dentsply, Maillefer, Ballaigues, Switzerland) was applied with an amplitude of 2 mm in up and down movements at a frequency of 100 strokes for 60 s, 1 mm shorter than the working length used in a previous study (18).

Visual Assessment Protocol

Upon completion of the irrigation procedures, each sample was observed under a dental operating microscope, and images were captured in JPEG format. All lateral canals were measured and transferred to ImageJ software (National Institutes of Health, Bethesda, USA). The depth of irrigation penetration into the lateral canal was scored using the following scoring system (19) (Fig. 2): Score 0: Lateral canal was empty, score 1: Contrast irrigation solution penetrated less than half of the lateral canal, score 2: Contrast irrigation solution penetrated more than half of the lateral canal, score 3: Contrast irrigation solution was observed to completely fill the lateral canal.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics software (version 29.0). Normality of data distribution was assessed using the Shapiro-Wilk test. Comparisons between groups were made using the Kruskal-Wallis and Mann-Whitney U tests. A p-value less than 0.05 was considered statistically significant.

Results

Table 1 shows the mean and standard deviation values of the groups. Statistical analysis revealed a significant difference between the irrigation activation techniques (p=0.002). In the XPFR group, the depth of penetration of the MB into the lateral canal was significantly less than in the EDDY (p=0.002) and MDA (p=0.008) groups. However, no significant difference in CIS penetration depth was observed between the EDDY and MDA groups (p=0.595).

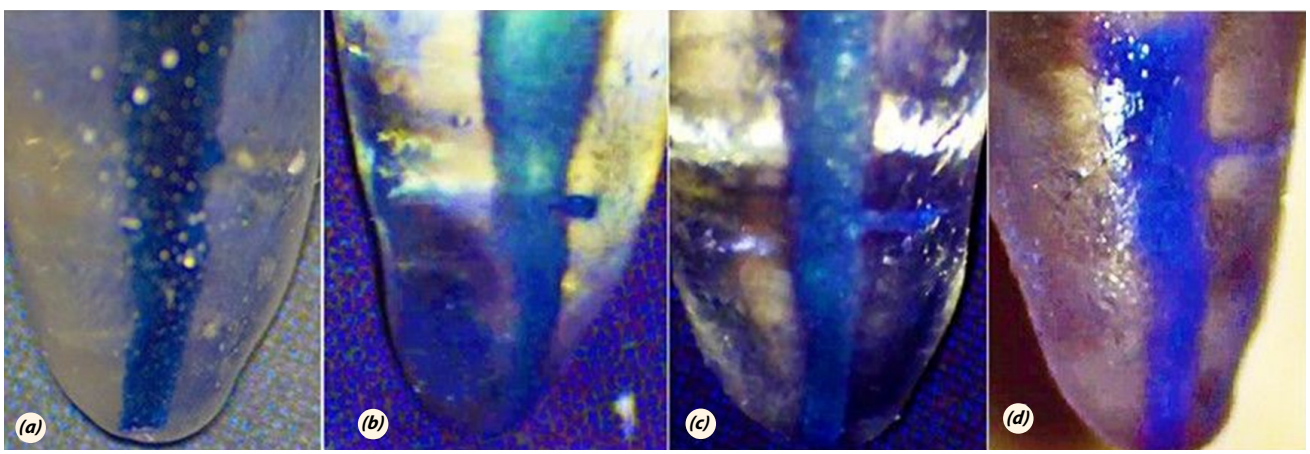

Fig. 2. Scoring System: **a-0:** Lateral canal was empty, **b-1:** Less than half of the lateral canal was filled with the contrast irrigation solution, **c-2:** Contrast irrigation solution covered more than half of the lateral canal, **d-3:** Contrast irrigation solution was observed to completely fill the lateral canal.

Table 1. Mean and standard deviation values of penetration scores of contrast irrigation solution in experimental groups

Irrigation Activation Techniques	Mean ± Standard Deviation
XP-Endo Finisher R	1.5333a±0.64
Manuel Dynamic Irrigation	2.4000b±0.83
EDDY	2.5333b±0.92

*p=0.002, Superscript letters indicate statistically significant differences between groups. (Mann Whitney U Test)

Discussion

Lateral canals, which often exit at various points along the root surface, serve as potential pathways for microbial invasion and may contribute to the development of apical periodontitis. Therefore, ensuring adequate disinfection of these anatomical extensions is particularly crucial in cases involving pulp necrosis or periapical infections. However, due to their narrow structure and complex positioning, achieving effective cleaning and decontamination of lateral canals remains a significant challenge (20).

In this study, resin blocks with simulated lateral canals were used to standardise the anatomy. Since it was not possible to create root canals with standardised dimensions due to variations in natural teeth, resin blocks were preferred. Previous studies have also shown that it is useful to use simulated artificial root canals to study irrigation efficacy (21-23). However, the use of simulated root canals has inherent limitations when compared to natural root canals, mainly because they do not replicate the dentin structure and the complex root canal morphology.

To address this, modern irrigation strategies have focused on enhancing irrigant distribution and penetration using activation techniques. Several studies have assessed the depth of irrigation solution penetration into lateral canals to evaluate the cleaning efficacy of different activation systems (16,24-26). Despite these investigations, comparative data on XPFR, EDDY, and MDA methods have remained scarce. Thus, the present in vitro study aimed to provide insight into how these three techniques influence irrigation solution penetration into simulated lateral canals within 3D-printed tooth models. Penetration was quantified using a direct visual scoring approach under magnification, following the protocol described by Fidan and Erdemir (25), who concluded that direct observation provided the most accurate assessment when compared to radiographic or tomographic imaging techniques.

In the current study, the XP-Endo Finisher R exhibited significantly less irrigation solution penetration into lateral canals than both the EDDY and MDA techniques. Therefore, the null hypothesis was rejected. While no prior research has directly evaluated XPFR in this specific context, a related investigation comparing the older XP-Endo Finisher with EDDY and laser-activated irrigation showed comparable results for the two techniques in terms of penetration at the 2 mm level of root canals (25). The lower performance of XPFR in the present study may be attributed to its direct contact with dentinal walls, particularly in the apical region. This contact may limit its oscillation and reduce the dynamic flow of irrigation solution, despite its high displacement amplitude.

The penetration depths achieved by EDDY and MDA were statistically similar, suggesting comparable performance. Although direct comparisons between these two techniques are limited, Donnermeyer et al. (24) evaluated their efficacy in hydrogel removal within curved canals and reported superior outcomes with EDDY. The discrepancies between the findings are likely due to the use of a different experimental methodology in that study. While their study focused on the removal of hydrogel from lateral canals in root canals with a 60-degree curvature, our study investigated the amount of irrigant penetration into lateral canals in straight root canal. Conversely, studies comparing MDA with other sonic activation devices such as the EndoActivator have produced controversial findings. Virdee et al. (27) found that MDA achieved greater penetration of sodium hypochlorite into dentinal tubules than both passive ultrasonic irrigation and the EndoActivator. In that study, the authors investigated the penetration of the irrigant into dentinal tubules in extracted teeth. In contrast, Solete et al. (28) observed inferior irrigant penetration with MDA in the apical third compared to sonic activation. In that study, the penetration of the irrigation solution into the apical region of extracted teeth was evaluated using radiological methods.

Alsubait et al. (29) in their study in which they investigated the removal of debris using EDDY, MDA and XPFR activation techniques, they found that the MDA technique was more unsuccessful than EDDY and XPFR methods. It is thought that the results of this study are different from our results due to the examination of mandibular molar teeth and the use of natural teeth instead of resin block teeth.

3D-printed tooth replicas were used in the current study under in vitro conditions. The use of 3D-printed tooth models, which have been employed in several research studies (11,12,15,18,30-32), offers a significant advantage by standardizing the dimensions of lateral root canals. This standardization enables more reproducible comparisons of different irrigation techniques, a level of

consistency that is difficult to achieve with extracted teeth. While this approach allows for reproducibility and consistent morphology, it does not fully replicate the anatomical variability of natural teeth, including features like apical deltas and complex lateral canal networks. Additionally, under the clinical conditions, the wettability of dentine, its surface energy, and the use of sodium hypochlorite may influence the penetration of irrigation solutions into the lateral canals. However, this experimental method is designed to measure how effectively irrigation activation techniques can mechanically deliver the solution into the lateral canal. Nonetheless, such models offer a reliable platform for comparative analysis of irrigation methods under uniform conditions.

Conclusion

The present study results suggest that EDDY and MDA demonstrated superior efficacy compared to XPFR in delivering the contrast irrigation solution into lateral canals. These results emphasize the importance of the irrigation activation method in enhancing irrigant distribution within anatomically complex regions of the root canal system. Further studies involving natural teeth and clinically relevant conditions are recommended to validate these outcomes.

Authorship Contributions: Concept: M.U., S.A.T.; Design: M.U., S.A.T.; Supervision: S.A.T.; Data: M.U.; Analysis: M.U., N.M.D., S.A.T.; Literature Search: M.U.; Writing: M.U., N.M.D.; Critical Revision: M.U., N.M.D., S.A.T.

Acknowledgements: *15th International Congress of Turkish Endodontics Association, Antalya, Türkiye, 21.05.2024.

Use of AI for Writing Assistance: The translation of the study into academic English was supported by Chat GPT.

Source of Funding: None declared.

Conflict of Interest: None declared.

Ethical Approval: The study was conducted on 3D-printed teeth, and since no human- or animal-derived samples or materials were used, obtaining ethical approval was not deemed necessary.

Informed consent: As this was an in vitro study utilizing 3D-printed models, formal informed consent was not required.

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