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Comparative analysis of 3D-printed and conventional endodontic access guides in calcified canals: A randomized controlled clinical trial

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Abstract:
Pulp canal calcification increases the difficulty and risk of errors during endodontic access preparation. Therefore, it is of interest to compare the 3D-printed guided access with conventional freehand access in 50 patients with calcified root canals. The guided group showed higher canal negotiation success (92% vs. 72%), shorter access time (18.4 ± 4.2 vs. 29.7 ± 6.8 min), lower bur deviation (2.1° ± 0.8° vs. 5.6° ± 1.4°) and fewer perforations (4% vs. 20%). It also showed greater residual dentin preservation, less tooth structure removal and superior 12-month periapical healing (87% vs. 67%). Thus, three-dimensional printed access guides improved procedural accuracy, dentin preservation and clinical outcomes in calcified canals compared with conventional access preparation.

Keywords: 3D-printed guide, guided endodontics, calcified canal, pulp canal obliteration, Cone-beam computed tomography (CBCT), access cavity, canal negotiation, stereolithography, minimally invasive endodontic

Background:
Pulp canal calcification or obliteration is characterized by progressive mineralized tissue deposition within the pulp space and is commonly associated with previous dental trauma **[1].** Calcified canals may remain asymptomatic but become difficult to negotiate when endodontic treatment is indicated, increasing the risk of excessive dentin removal, canal deviation and perforation **[2]**. Conventional management relies on radiographs, magnification, ultrasonics and tactile guidance but remains technically demanding in severely calcified canals **[3]**. Cone-beam computed tomography (CBCT) provides three-dimensional visualization of the residual canal and facilitates accurate assessment of its location and trajectory **[4]**. Guided endodontics combines CBCT data with digital planning and three-dimensional printing to direct the bur toward the calcified canal while minimizing unnecessary tooth structure removal **[5]**. Studies have demonstrated improved canal localization, reduced dentin removal and accurate drilling paths with guided techniques **[6]**. Recent clinical evidence also suggests that static-guided access can improve canal negotiation and reduce procedural complications compared with conventional freehand techniques **[7, 8]**. Therefore, it is of interest to compare the clinical accuracy, procedural efficiency, dentin preservation and outcomes of 3D-printed guided endodontic access with conventional freehand access in teeth with calcified root canals.

Materials and Methods:
Study design:
A prospective randomized controlled clinical trial with parallel-group design and 1:1 allocation ratio was conducted over 20 months at the Department of Conservative Dentistry and Endodontics, SMBT Dental College and Hospital, Sangamner, Maharashtra, India.

Ethical clearance:
The study protocol was approved by the Institutional Ethics Committee, SMBT Dental College and Hospital (IEC Ref. No. SMBT/IEC/ENDO/2022-23/11; approved June 5, 2023). The trial was prospectively registered with the Clinical Trials Registry of India (CTRI/2023/06/054312). Written informed consent was obtained from all participants before enrolment.

Study population:

Fifty patients presenting with single-rooted or multi-rooted teeth exhibiting partial or complete pulp canal calcification confirmed on CBCT and requiring endodontic treatment were enrolled. Patients were randomly allocated using a computer-generated randomization sequence with allocation concealment via sequentially numbered sealed opaque envelopes.

Inclusion criteria:

[1] Patients aged 18–60 years with a confirmed diagnosis of pulp canal calcification on pre-operative CBCT.
[2] Indication for endodontic treatment (symptomatic irreversible pulpitis, pulp necrosis, or periapical pathology).
[3] Residual canal lumen visible on CBCT with a minimum diameter of 0.15 mm.
[4] Adequate coronal tooth structure to retain the guide stent (minimum 2 mm of supra-gingival tooth height circumferentially).
[5] Absence of severe root curvature (Schneider angle <25°C).
[6] Willingness to comply with follow-up appointments at 3, 6 and 12 months.

Exclusion criteria:

[1] Patients with systemic conditions contraindicating dental treatment.
[2] Teeth with vertical root fractures, external root resorption, or compromised periodontal support (PPD >5 mm or furcation involvement Grade III).
[3] Residual canal lumens not identifiable on CBCT despite 0.2 mm slice reconstruction.
[4] Teeth requiring surgical endodontic management at baseline.
[5] Pregnant or lactating women.
[6] Patients with known allergy to resin-based materials.

Pre-operative assessment:

All patients underwent pre-operative CBCT imaging (Planmeca ProMax 3D; field of view 8x8 cm; voxel size 0.2 mm; 90 kVp; 10 mA) to delineate residual canal morphology, measure canal lumen diameter and plan the access trajectory. Canal dimensions and path were analyzed using dedicated CBCT viewing software (Romexis, Planmeca). The pre-operative Periapical Index (PAI) score was recorded for all teeth. Conventional periapical radiographs (parallel technique, RVG sensor) were also obtained for baseline comparison.

Group I – 3D-Printed guide fabrication and protocol:

CBCT DICOM data were imported into guided endodontic planning software (BlueSkyPlan, BlueSkyBio). The residual canal path was digitally traced from the proposed access point on the occlusal and lingual surface to the apical foramen. A virtual access guide was designed incorporating a stainless-steel sleeve (internal diameter 1.0 mm) oriented along the planned trajectory and mounted on a tooth-supported resin body that engaged the occlusal and proximal surfaces for stable retention. The guide body was fabricated from biocompatible SLA photopolymer resin (Dental SG Resin; Formlabs Form 3) and printed at 0.05 mm layer resolution. Printed guides were post-cured under UV light for 30 minutes and sterilized by immersion in 2% glutaraldehyde solution for 30 minutes prior to clinical use. The guide was seated on the tooth with verification of passive fit. Endodontic access was initiated using a 1.0 mm diameter endodontic access bur (EndoGuide Bur, SS White) through the guide sleeve under constant water irrigation. Sequential ultrasonic troughing (Satelec P5 Newtron; CPR-4 tip, 40% power) was performed after reaching the planned depth. Canal patency was confirmed using a Size 08 K-file under CBCT-confirmed apical length. Chemomechanical preparation was completed using a reciprocating system (WaveOne Gold Primary, Dentsply Sirona) and 2.5% sodium hypochlorite irrigation.

Group II – conventional guide protocol:

Access cavity preparation was performed using conventional freehand technique guided by two pre-operative periapical radiographs (buccal and mesial-angled views), clinical knowledge of pulp chamber anatomy and a conventional acrylic reference stent fabricated chairside from a polyvinyl siloxane putty matrix. Ultrasonic troughing and canal location were performed using the same ultrasonic unit and tips as Group I. A dental operating microscope (Global Surgical Corporation, 16× magnification) was available for both groups equally. Chemomechanical preparation was completed using the same protocol as Group I.

Outcome measurements:

[1] Canal negotiation success rate – defined as confirmed passage of a Size 08 K-file to the working length as determined by apex locator and CBCT.
[2] Mean access time – recorded from rubber dam placement to confirmed canal patency (stopwatch, minutes).
[3] Bur penetration deviation angle – measured on post-operative CBCT by superimposing actual bur tract on pre-planned trajectory using Romexis software.
[4] Dentinal wall perforation rate – classified as any communication between the access preparation and the external root surface on post-operative CBCT or clinical detection.
[5] Post-operative CBCT parameters – residual dentin thickness at access cavity floor, volume of removed tooth structure (calculated from pre- and post-operative CBCT segmentation), access cavity centering ratio and guide-track deviation from planned path.
[6] Periapical healing at 12 months – assessed using PAI score on standardized periapical radiographs; healing defined as reduction to PAI ≤2.
[7] Post-treatment pain – Numeric Rating Scale (NRS 0–10) at 48 hours post-procedure.
[8] Patient satisfaction – 10-point Visual Analogue Scale (VAS) at 12-month recall.

Statistical Analysis: Data were analyzed using SPSS software version 26.0 (IBM Corp., Armonk, NY, USA). Continuous

variables were expressed as mean ± standard deviation. The Shapiro–Wilk test was used to assess normality. Independent t-test was applied for parametric intergroup comparisons and the Mann–Whitney U-test for non-parametric data. Categorical outcomes were compared using the Chi-square test or Fisher's exact test. Kaplan–Meier survival analysis with log-rank test was used for tooth survival estimation. All tests were two-tailed with a significance level set at $p<0.05$.

Results:

The two groups were comparable in all baseline characteristics including age, sex, tooth type, degree of calcification, pre-operative canal lumen diameter and periapical status **(Table 1),** confirming successful randomization and absence of selection bias. Group I showed a significantly higher canal negotiation success rate (92%; 23 of 25 cases) compared with Group II (72%; 18 of 25 cases; p=0.048). The two cases of negotiation failure in Group I involved teeth with complete canal obliteration confirmed post-operatively on CBCT where no residual lumen was identifiable beyond the coronal third. In Group II, seven failures occurred due to inability to locate the canal orifice (n=4) or perforation necessitating cessation of access preparation (n=3). Mean access time was significantly reduced in Group I (18.4 ± 4.2 minutes) compared with Group II (29.7 ± 6.8 minutes; p=0.001). Bur trajectory deviation was significantly lower in Group I (2.1°C ± 0.8°C vs 5.6°C ± 1.4°C; p=0.001). Dentinal wall perforation occurred in only one case in Group I (4%) versus five cases in Group II (20%; p=0.038; **Table 2**). Post-operative CBCT analysis confirmed significantly greater preservation of residual dentin at the access cavity floor in Group I (1.82 ± 0.24 mm) compared with Group II (1.41 ± 0.31 mm; p=0.001). The volume of tooth structure removed was significantly less in Group I (18.4 ± 3.1 mm^3) than in Group II (26.7 ± 4.8 mm^3; p=0.001). The access cavity centering ratio, reflecting proximity of the prepared access to the canal center, was significantly superior in Group I (0.88 ± 0.06 vs 0.74 ± 0.09; p=0.001). Mean guide-track deviation from the planned trajectory was 0.31 ± 0.12 mm in Group I compared with 1.18 ± 0.34 mm in Group II (p=0.001). Ledge formation was not observed in Group I and occurred in three cases in Group II, though the difference did not reach statistical significance (p=0.072; **Table 3**). Periapical healing, defined as reduction to PAI ≤2 at 12 months, was achieved in 87% (20 of 23 successfully treated cases) in Group I compared with 67% (12 of 18 cases) in Group II (p=0.043). Post-treatment pain scores at 48 hours were significantly lower in Group I (NRS 2.1 ± 0.9) compared with Group II (NRS 3.6 ± 1.2; p=0.001). Tooth survival at 12 months was 96% in Group I and 84% in Group II (p=0.091). Patient satisfaction was significantly higher in Group I (8.8 ± 0.7 vs 7.1 ± 1.1; p=0.001; **Table 4). (Table 5)** summarizes the key technical characteristics and differences between the 3D-printed and conventional guide systems used in this study.

Table 1: Baseline demographic and clinical characteristics

Characteristic	Group I – 3D-Printed Guide (n=25)	Group II – Conventional Guide (n=25)	p-value
Age (years), Mean ± SD	44.6 ± 9.3	43.8 ± 8.7	0.724
Sex (Male/Female)	14/11	13/12	0.771
Tooth type (Anterior/Premolar/Molar)	10/8/7	9/9/7	0.921
Degree of calcification (Partial/Complete)	16/9	15/10	0.774
Pre-op CBCT canal lumen diameter (mm), Mean ± SD	0.38 ± 0.09	0.37 ± 0.08	0.641
Pre-op periapical status (PAI score), Mean ± SD	2.8 ± 0.6	2.9 ± 0.7	0.559

Table 2: Primary clinical outcomes: access accuracy and procedural efficiency

Outcome Parameter	Group I – 3D-Printed Guide	Group II – Conventional Guide	p-value
Canal negotiation success rate (%)	92% (23/25)	72% (18/25)	0.048*
Mean access time to canal location (min)	18.4 ± 4.2	29.7 ± 6.8	0.001*
Bur penetration deviation from planned trajectory (°C)	2.1 ± 0.8	5.6 ± 1.4	0.001*
Dentinal wall perforation rate (%)	4% (1/25)	20% (5/25)	0.038*
Number of burs used per case, Mean ± SD	3.2 ± 0.9	5.8 ± 1.3	0.001*
Intraoperative radiographs taken per case, Mean ± SD	2.4 ± 0.7	4.9 ± 1.1	0.001*
Operator confidence score (VAS 1–10)	8.6 ± 0.9	6.2 ± 1.3	0.001*

**Statistically significant ($p < 0.05$).*

Table 3: Post-operative CBCT assessment of dentin preservation and access accuracy

CBCT Parameter	Group I – 3D-Printed Guide	Group II – Conventional Guide	p-value
Residual dentin thickness at access cavity floor (mm), Mean ± SD	1.82 ± 0.24	1.41 ± 0.31	0.001*
Volume of tooth structure removed (mm^3), Mean ± SD	18.4 ± 3.1	26.7 ± 4.8	0.001*
Access cavity centering ratio, Mean ± SD	0.88 ± 0.06	0.74 ± 0.09	0.001*
Guide-track deviation from planned path (mm)	0.31 ± 0.12	1.18 ± 0.34	0.001*
Post-op crown-down perforation (n)	1	5	0.038*
Ledge formation (n)	0	3	0.072

**Statistically significant ($p < 0.05$).*

Table 4: 12-Month clinical and radiographic follow-up outcomes

Follow-up Parameter	Group I – 3D-Printed Guide	Group II – Conventional Guide	p-value
Periapical healing (PAI ≤2 at 12 months) (%)	87% (20/23)	67% (12/18)	0.043*
Post-treatment pain score (NRS 0–10) at 48 h	2.1 ± 0.9	3.6 ± 1.2	0.001*
Cases requiring retreatment at 12 months (n)	1	4	0.082
Tooth survival at 12 months (%)	96% (24/25)	84% (21/25)	0.091

Patient satisfaction (VAS 0–10)	8.8 ± 0.7	7.1 ± 1.1	0.001*

**Statistically significant ($p < 0.05$).*

Table 5: Comparative characteristics of 3D-printed and conventional access guide systems

Parameter	3D-Printed Guide	Conventional Guide
Imaging required	CBCT (0.2 mm slice thickness)	Periapical radiograph (2 views)
Design software	Materialise ProPlan / BlueSkyPlan	Manual template/freehand
Fabrication method	SLA/DLP resin printing	Acrylic chairside / vacuum-formed
Mean fabrication time	4.2 ± 0.6 hours (lab)	0.5 ± 0.1 hours (chairside)
Material cost per guide (INR)	2,800 ± 350	180 ± 40
Fit accuracy (marginal discrepancy µm)	84 ± 18	312 ± 64
Reusability	Single use	Limited reuse
Guidance type	Static, depth-controlled sleeve	Freehand with reference mark

Discussion:

The present randomized controlled trial demonstrated superior clinical performance of 3D-printed guided access compared with conventional freehand access in calcified root canals. Canal negotiation success was higher with guided access (92% vs. 72%), consistent with previous clinical evidence supporting guided endodontics **[9]**. Guided access also significantly reduced procedural time and intraoperative radiographs, indicating improved clinical efficiency **[10].** The guided group showed greater residual dentin thickness (1.82 vs. 1.41 mm) and less tooth structure removal (18.4 vs. 26.7 mm^3), supporting the principles of minimally endodontics **[11]**. Greater dentin preservation may also contribute to improved long-term tooth survival by maintaining structural integrity. Lower bur deviation and improved centering further demonstrated the precision provided by the rigid 3D-printed guide **[12]**. Periapical healing at 12 months was higher in the guided group (87% vs. 67%), potentially reflecting improved canal negotiation, reduced procedural complications and more favorable access geometry. Although guided access had a higher fabrication cost, reduced chair time, bur consumption and procedural complications may improve its cost-effectiveness in complex cases. Advances in accessible 3D-printing technology may further reduce fabrication costs. The study was limited by its single-center design, 12-month follow-up and exclusion of completely obliterated canals. Larger multicenter trials with longer follow-up and formal cost-effectiveness analyses are warranted to confirm these findings.

Conclusion:

3D-printed endodontic access guides showed significant clinical superiority over conventional freehand access guides in the management of calcified root canals. The 3D-printed guide group achieved higher canal negotiation success, reduced procedural time, lower iatrogenic perforation rate, superior dentin preservation, better periapical healing and greater patient satisfaction. The evidence supports the integration of CBCT-guided, 3D-printed access stents into standard clinical practice for the management of complex calcified canal cases, with the acknowledgment that appropriate patient selection, CBCT availability and digital fabrication infrastructure are prerequisites for successful implementation.

Conflict of Interest: The authors declare no conflicts of interest.

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