

Custom Sleeve Parameters in Static Guided Endodontic Access: Influence on Deviation Control in Pulp Canal Obliteration

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Purpose: Pulp canal obliteration (PCO) narrows the root canal, complicating access and increasing treatment risks. This study aims to evaluate the accuracy of static guided endodontic access (SGEA) using custom sleeves of different materials and heights compared to conventional freehand access (FHA) in pulp canal obliteration.

Methods: An in vitro experimental study was conducted using 48 resin maxillary incisors modeled to simulate pulp canal obliteration via CBCT, intraoral scanner, and 3D printing. The samples were divided into eight groups (n=6): a negative control (freehand access-FHA), a positive control (Titanium Steco 5 mm sleeve), and six static guided endodontic access (SGEA) groups using custom inner sleeves made of Chrome-Cobalt (CoCr) and Zirconia at three heights (3 mm, 5 mm, and 7 mm). Coronal and sagittal deviations between pre- and postoperative CBCT scans were analyzed using one-way ANOVA and Bonferroni post hoc tests ($\alpha=0.05$).

Results: All SGEA groups demonstrated significantly lower deviation values compared to freehand access ($p < 0.05$). The mean coronal deviation ranged from 1.83° to 6.90°, with the lowest value observed in the Zirconia 7 mm sleeve group (1.83°±1.84°). Sagittal deviation ranged from 2.48° to 30.08°, also lowest in the Zirconia 7 mm group (2.48°±2.43°) and highest in the freehand access group (30.08°±5.93°). Increased sleeve height improved angular precision, and zirconia demonstrated superior dimensional stability compared to chrome-cobalt and titanium.

Conclusion: The SGEA technique provided higher accuracy than freehand access in controlling drilling deviation. Among the tested parameters, the custom 3D-printed zirconia sleeve with a 7 mm height yielded the best precision, supporting its potential use in minimizing iatrogenic risk during endodontic access of obliterated canals. This in vitro study on resin models requires further in vivo validation for clinical application.

Plain Language Summary: Sometimes, after trauma or over time, a tooth's root canal becomes blocked by hard tissue, making it difficult for dentists to locate and treat. This study evaluated whether using a 3D-printed guide enables dentists to achieve greater drilling precision than the conventional freehand technique. Model teeth with blocked canals were prepared using different guide materials (metal, zirconia, and titanium) and sleeve heights (3 mm, 5 mm, and 7 mm). The results showed that guided techniques were much more accurate than freehand drilling, especially when using longer zirconia sleeves. The current study found guided endodontics can help reduce the risk of drilling errors, preserve more healthy tooth structure, and make treatment safer and more predictable for patients with pulp canal obliteration.

Keywords: guided endodontics, pulp canal obliteration, 3D printing, custom sleeve design, minimally invasive endodontics, deviation control

Introduction

Pulp canal obliteration (PCO), or calcific metamorphosis, frequently follows trauma, orthodontic forces, or other stimuli, producing tertiary dentin that narrows or blocks the canal lumen.¹ Its incidence after dental trauma ranges from 3.7% to over 30%, and affected teeth may later require root canal treatment.² Pulp canal obliteration (PCO) often follows concussion or luxation trauma of anterior teeth, resulting from hard tissue deposition within the canal. It typically appears within 3–12 months post-injury, underscoring the need for long-term follow-up to detect pulpal or periapical changes.^{3,4} Conventional freehand access in PCO is difficult, risking excessive dentin loss or perforation, with failure rates approaching 20%.⁵ Although minimally invasive endodontics promotes tooth preservation, achieving straight-line access in calcified canals remains challenging.^{6–9}

Guided endodontics integrates CBCT-based planning and 3D-printed static templates to guide the drill precisely to the canal path.^{5,10} Studies consistently show higher accuracy and safety than freehand techniques, with fewer perforations and reduced angular deviation.^{8,11} A large clinical series found no perforations with guided access versus multiple perforations in freehand cases, yielding a significantly better outcome with guidance ($p < 0.05$).^{6,12,13} Meta-analyses confirm its superior precision and lower iatrogenic risk.^{14,15} Nevertheless, a study gap remains regarding the optimization of sleeve parameters, particularly the material composition and sleeve height variations, which may affect guidance accuracy, heat generation, and drill stability during static-guided endodontic procedures.

Recent static-guided endodontic systems, such as the Steco guide endodontic system (Germany) integrate CBCT and 3D printing for accurate canal access.^{10,16,17} However, these systems are costly, less accessible, and not optimized for endodontic access. Titanium may also cause radiographic scatter that limits canal visibility. These systems rely on proprietary metallic sleeves and offer limited customization. Inspired by implant-guided technology, custom 3D-printed or sleeveless designs may provide similar precision.^{18–20} Dentin fragility and restricted space prevent implant ideas from being applied in endodontics. The lack of biomechanical data on endodontic sleeves led this work to investigate CoCr and zirconia sleeve materials and their height changes to improve guiding accuracy. Drill deviation should decrease with longer, harder sleeves.

Although guided endodontics improves precision in treating obliterated canals, limitations remain regarding high cost, dependence on CBCT image quality, extended digital planning time, and restricted access in posterior teeth. Additionally, variations in sleeve height and material may affect drill stability and maneuverability. These constraints, already noted in the literature, are acknowledged to prevent confirmation bias in this study.²¹ This study aimed to compare the accuracy of minimally invasive guided endodontic access using custom 3D-printed sleeves of different materials (titanium, CoCr alloy, and zirconia) and heights (3, 5, and 7 mm) versus conventional freehand access in pulp canal obliteration.

Materials and Methods

This research was conducted following approval from the Institutional Review Board and the local ethics committee of Padjadjaran University (Approval No. 194/UN6.KEP/EC/2025). [Figure 1](#) illustrates the configuration of the study.

Stage I

The files were radiographed using a CBCT (OP300 Maxio, KAVO, Finland) with dimensions of 600×600 x 312 mm, voxel spacing of 0.25 x 0.25×0.25 mm, and a slice thickness of 0.25 mm ([Figure 2a](#)). Employing the CEREC Primescan intraoral scanner (Dentsply Sirona, Germany) to get intricate canal geometry via surface scanning ([Figure 2b](#)). Files were exported and converted into Standard Tessellation Language (STL) files using Meshmixer Version 3.5.474 (<https://meshmixer.org/>) for segmentation graphics ([Figure 2c](#)). Through this treatment, artificial pulp canal obliteration was performed on the midsection of the maxillary left central incisor. STL files were generated for fabrication using a Formlabs 4 printer (Formlabs, USA) to produce 48 transparent resin incisor teeth ([Figure 2d](#)). The teeth were printed from transparent resin to ensure accurate sizing and clear visibility. The Young's Modulus (about 2.7–3.0 GPa) is inferior to that of genuine dentin (approximately 12–18 GPa),²². However, its uniform mechanical properties make it suitable for systematic in vitro evaluations of drilling precision. The fabricated resin teeth were then mounted in dental arch simulators (four maxillary jaw models) on a dental training phantom (Trimunt ARISTA TA-500, Japan) to reproduce clinical orientation ([Figure 2e](#)). Each tooth was fixed in a resin base (2 mm thickness) with the root portion exposed for CBCT scanning, using a FOV of 8×8 cm (OP300 Maxio, KAVO, Finland)

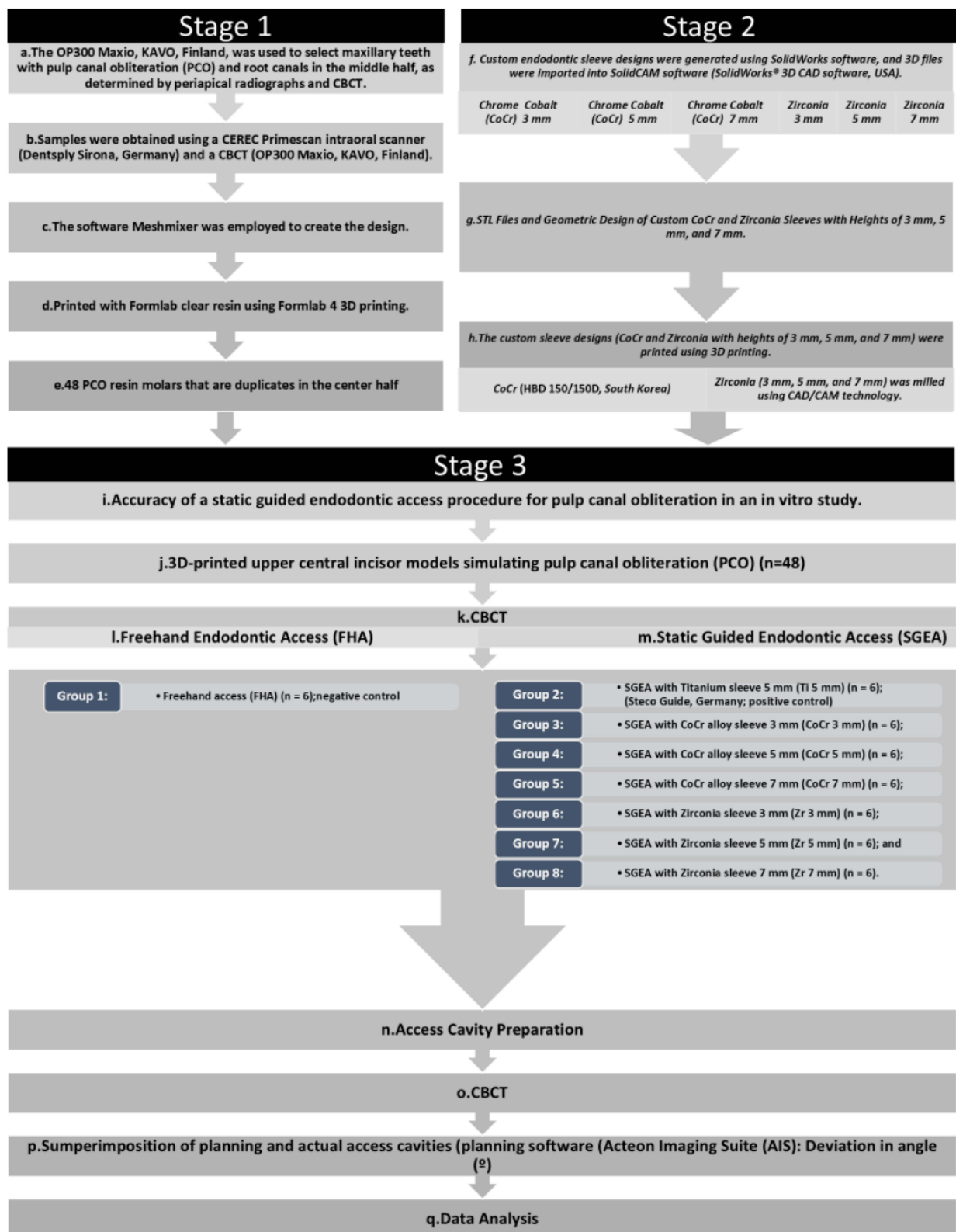


Figure 1 Study design.

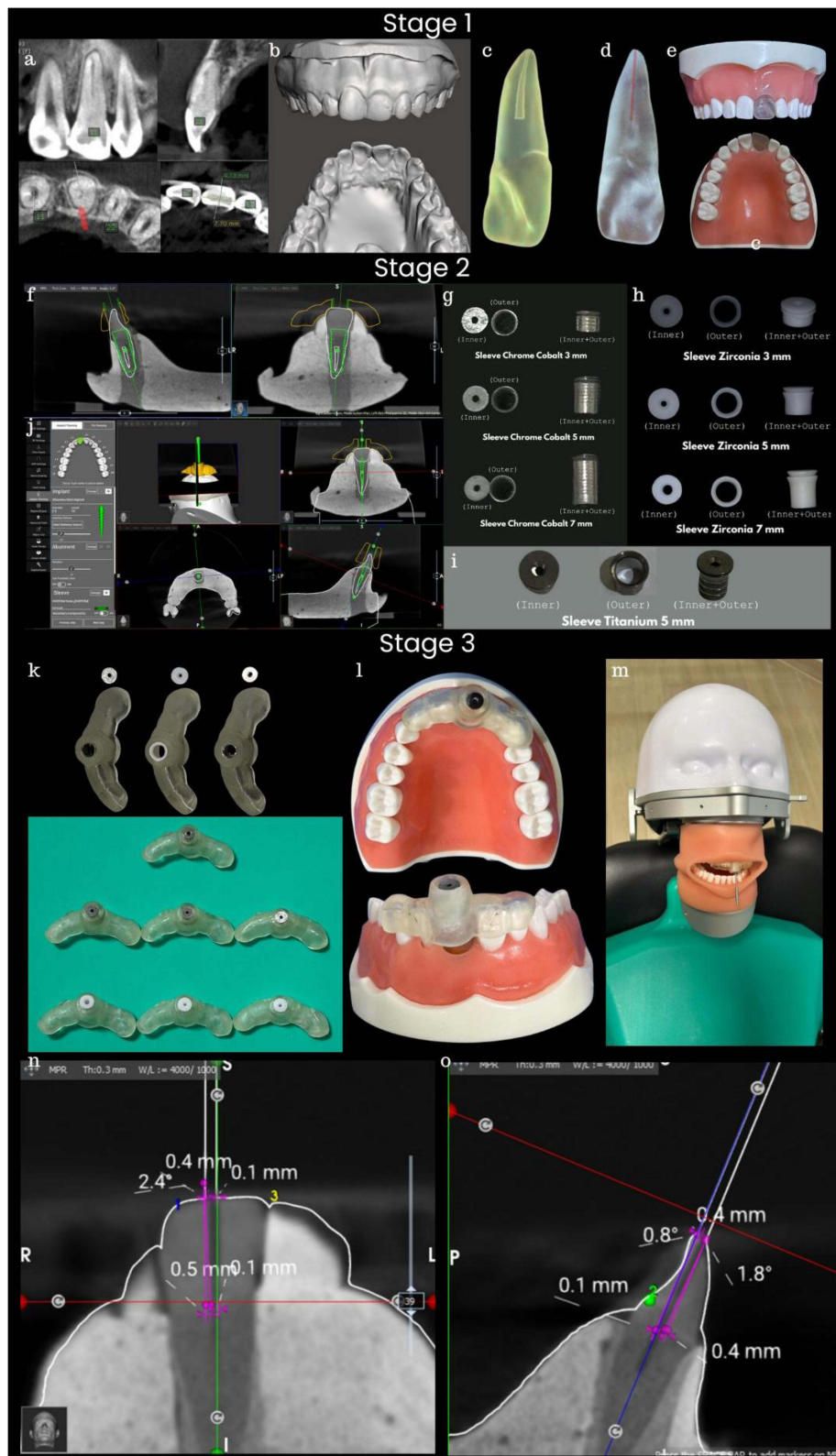


Figure 2 Guided endodontic workflow and deviation analysis, (a) Pre-operative CBCT and (b) intraoral scan acquisition, (c) Pulp canal obliteration resin tooth design results with Meshmixer software and (d) 3D-printed transparent tooth simulating canal obliteration, (e and f) Phantom mounting and baseline CBCT, (g–i) Fabrication of custom CoCr, zirconia, and prefabricated titanium sleeves, (j) 3D-printed static guided endodontic templates with press-fit sleeves, (k and l) Guided access using 1.0-mm bur under irrigation, and (m–o) Postoperative CBCT superimposition and coronal/sagittal deviation assessment at the canal orifice.

(Figure 2f). This in vitro study used standardized resin tooth models to ensure reproducibility and control canal geometry. Although artificial teeth are acceptable for such studies, they lack the biological properties of natural dentin and supporting tissues, limiting direct clinical extrapolation. Nonetheless, this approach enables precise and consistent assessment under controlled conditions.

Stage 2

Custom sleeves were designed in SolidWorks® CAD software (USA) with an inner channel matching the 1.0 mm drill diameter. Three sleeve heights (3 mm, 5 mm, and 7 mm) were modeled to assess stability. The designs incorporated inner and outer sleeve structures and were exported as STL files for fabrication. The custom CoCr (Starbond CoS Powder 30; Co 59%, Cr 25%, W 9.5%, Mo 3.5%) sleeves were designed and fabricated using 3D printer (HBD 150/150D, China) (Figure 2g), and zirconia (IPS e.max ZirCAD, Ivoclar) sleeves were designed and fabricated using CEREC CAD/CAM-Milling (Dentsply Sirona, Germany) (Figure 2h). A prefabricated 5 mm titanium sleeve (Steco Guide, Germany) served as the positive control (Figure 2i).

Using the digitized tooth model, access paths were planned with implant planning software (Acteon Imaging Suite (AIS) 3D, Acteon Group, Italy) to reach the canal orifice at an appropriate entry angle. A static guided endodontic template is designed in the planning software to fit the arch of the tooth. For guided groups, an STL design custom sleeve guided endodontic inner drill guide sleeve was placed coaxially. All SGEA templates were 3D-printed on a Formlabs 4 printer (Formlabs, USA), and custom-printed sleeves were press-fit or bonded into the SGEA template with the correct orientation (Figure 2j).

Stage 3

Each sleeve was press-fitted into the 3D-printed static guided endodontic access (SGEA) template with verified coaxial alignment (Figure 2k) and was divided into eight experimental groups (n = 6 per group). The group distribution was as follows:

- Group 1: Freehand Endodontic Access (FHA) (n = 6); negative control
- Group 2: Static Guided Endodontic Access (SGEA) with Titanium sleeve 5 mm (Ti 5 mm) (n = 6); (Steco Guide, Germany; positive control)
- Group 3: SGEA with CoCr alloy sleeve 3 mm (CoCr 3 mm) (n = 6);
- Group 4: SGEA with CoCr alloy sleeve 5 mm (CoCr 5 mm) (n = 6);
- Group 5: SGEA with CoCr alloy sleeve 7 mm (CoCr 7 mm) (n = 6);
- Group 6: SGEA with Zirconia sleeve 3 mm (Zr 3 mm) (n = 6);
- Group 7: SGEA with Zirconia sleeve 5 mm (Zr 5 mm) (n = 6); and
- Group 8: SGEA with Zirconia sleeve 7 mm (Zr 7 mm) (n = 6).

The SGEA template was seated on the model, and guided access was performed using a 1.0 mm endodontic bur (Steco system, Germany) (Figure 2L), using a low-speed handpiece operated at 700–1000 rpm with a torque of ~2.5 Ncm (0.25 Nm) with constant irrigation. The guide constrained the bur within the sleeve (Figure 2m). For freehand controls, no guide was used; the bur was directed by eye and microscope to approximate the planned path. A single operator (experienced endodontist) performed all accesses to minimize variability. The single operator was pre-calibrated through training on pilot samples to ensure procedural consistency and accuracy.

After access preparation, a second CBCT, FOV 8×8 cm (OP300 Maxio, KAVO, Finland) was obtained for each tooth. Pre- and postoperative CBCT datasets were superimposed using ACTEON Imaging Suite (AIS System, Italy) and registered at three landmarks: the incisal edge, cervical region, and apex for precise alignment. Coronal (labio-lingual) (Figure 2n) and sagittal (mesio-distal) (Figure 2o) deviations at the canal orifice were measured. Two calibrated, blinded examiners performed the assessments, with inter- and intra-examiner reliability confirmed by an Intraclass Correlation Coefficient (ICC > 0.90), indicating excellent agreement.

Statistical Analysis

The sample size ($n = 6$ per group) was calculated using G*Power 3.1 with a large effect size ($f = 0.40$), $\alpha = 0.10$, and power = 0.90. As a pilot study, this number was deemed adequate to provide preliminary data for future investigations. In this study, each group included six samples, resulting in a total of 48 specimens across eight groups. Deviation data (degrees) were summarized as mean \pm SD. Normality was confirmed by Shapiro–Wilk test. A one-way ANOVA was used to compare the mean deviations across all groups. Significant ANOVA results ($p < 0.05$) were followed by Bonferroni post-hoc tests to identify pairwise differences. All analyses were performed in SPSS v25.

Results

All guided access procedures successfully reached the canal orifice without perforation. Six samples from each of the eight categories were analyzed. Data followed a normal distribution (Shapiro–Wilk, $p > 0.05$). One-way ANOVA was performed to compare mean coronal and sagittal deviations among groups, followed by Bonferroni post hoc tests for pairwise comparisons. Intra-group variability was expressed as mean \pm SD. Significant differences were found for coronal ($p < 0.01$) and sagittal ($p < 0.001$) deviations, with exact p-values presented in the results section and Table 1 for transparency (Table 1, Figures 3 and 4).

The variations in coronal deviations (Table 1, Figures 2n and 3) went from $1.83^\circ \pm 1.84^\circ$ (zirconia 7 mm) to $6.90^\circ \pm 2.03^\circ$ (CoCr 5 mm). The 7 mm zirconia sleeve had the best coronal accuracy of all the SGEA groups, as illustrated by its minimal mean deviation. The mean deviation for CoCr 5 mm was the highest, although it was still substantially lower than the mean deviation for the freehand group. The sagittal deviations (Table 1, Figures 2o and 4) showed that using guided sleeves significantly reduced the deviations, from $2.48^\circ \pm 2.43^\circ$ (zirconia 7 mm) to $30.08^\circ \pm 5.93^\circ$ (FHA). The FHA was divided into 3 mm, 5 mm, and 7 mm depths to compare deviation patterns at each drilling stage, with each step digitally superimposed on the virtual plan to evaluate progressive accuracy against the guided access groups. The sleeve was divided into 3 mm, 5 mm, and 7 mm depths to compare deviation patterns at each drilling stage, with each step digitally superimposed on the virtual plan to evaluate progressive accuracy against the guided access groups. The pairwise post-hoc analysis revealed that the zirconia 7 mm group was the only one that was significantly distinct from the freehand technique ($p < 0.05$). This finding suggests that the setup improved the accuracy of the process. In general, SGEA caused far fewer changes in angles than freehand access did in both the coronal and sagittal planes ($p < 0.05$). In simulated damaged canal scenarios, 7 mm zirconia consistently yielded the most precise results while minimizing iatrogenic risk.

Discussion

The present study confirms that static-guided access provides a significant accuracy advantage over freehand techniques in a PCO model.^{22,23} These findings align with prior clinical and in vitro investigations reporting sub-millimetric terminal deviations and reduced dentin removal with guided methods.^{24–27} Preservation of pericervical dentin is central to minimally invasive endodontics, and our data demonstrate that guided access reduces cavity volume by more than 60% relative to freehand, which supports tooth structural integrity.^{9,28–30} This conservation is particularly relevant in calcified anterior teeth, where canal location often requires extensive trephination with freehand methods.^{1,26,31}

Regarding sleeve material, zirconia outperformed CoCr (and performed at least as well as titanium control). At a height of 7 mm, zirconia sleeves resulted in significantly smaller coronal and sagittal deviations compared to CoCr or freehand methods. Zirconia's high stiffness (elastic modulus ~ 200 GPa) likely reduces elastic deflection under lateral drill forces. In contrast, the CoCr alloy (with an elastic modulus of ~ 220 GPa) is also stiff. However, current results suggest a slight material effect: the 5 mm titanium control (hard alloy) had a coronal error of $\sim 4.1^\circ$, similar to the CoCr 3 mm (3.7°) but less than the CoCr 5 mm (6.9°). This result hints that both material and precise sleeve fit influence accuracy. Published implant literature indicates that removing metal sleeves from guides does not always compromise accuracy.¹⁹ However, in endodontics, where drill contact is prolonged and the tunnel is narrow, even small deflections can be significant. In our study, zirconia sleeves achieved the tightest guidance. Future investigations could quantify sleeve wear or clearance tolerance, but our data suggest that choosing a hard, wear-resistant material (zirconia) benefits accuracy.

Table I Summary and Comparison of Coronal and Sagittal Angular Deviation (°) for Each Experimental Group Based on Sleeve Material and Height Variation

			Titanium 5mm (n=7)	Zirconia 3mm (n=6)	Zirconia 5mm (n=6)	Zirconia 7mm (n=6)	CoCr 3mm (n=6)	CoCr 5mm (n=6)	CoCr 7mm (n=6)	FHA 3mm (n=6)	FHA 5mm (n=6)	FHA 7mm (n=6)
ANGLE OF DEVIATION	Coronal	Average±SD	4.08±2.30	4.51±1.53	4.76±0.75	1.83±1.84	3.70±2.79	6.90±2.03	5.38±1.45	3.10±1.34	4.30±1.50	4.25±1.05
		Median (Min-Maks)	4.50 (1.50–6.80)	4.70 (1.90–6.50)	4.95 (3.30–5.50)	1.35 (0.10–4.00)	3.50 (0.00–7.40)	6.25 (5.00–9.80)	5.95 (3.30–6.80)	3.10 (1.40–5.00)	4.25 (2.50–6.60)	4.35 (2.50–5.70)
	<i>p-value</i>	0.002										
	Sagittal	Average±SD	3.62±0.80	4.01±0.70	3.85±1.15	2.48±2.43	4.05±2.80	5.95±0.91	5.91±2.73	30.08±5.93	29.18±5.27	29.15±4.49
Median (Min-Maks)		3.60 (2.30–4.50)	3.85 (3.30–5.10)	3.70 (2.70–5.90)	1.65 (0.40–5.50)	3.45 (1.10–9.30)	6.40 (4.60–6.80)	5.60 (2.20–10.50)	28.90 (22.80–40.20)	28.15 (21.50–37.10)	29.40 (21.40–35.10)	
<i>p-value</i>	<0.001											

Notes: Analysis of the mean difference in normally distributed numerical data was conducted using the One-Way ANOVA test, with a significance level of $p < 0.05$. The Bonferroni post-hoc test will be conducted if $p < 0.05$.

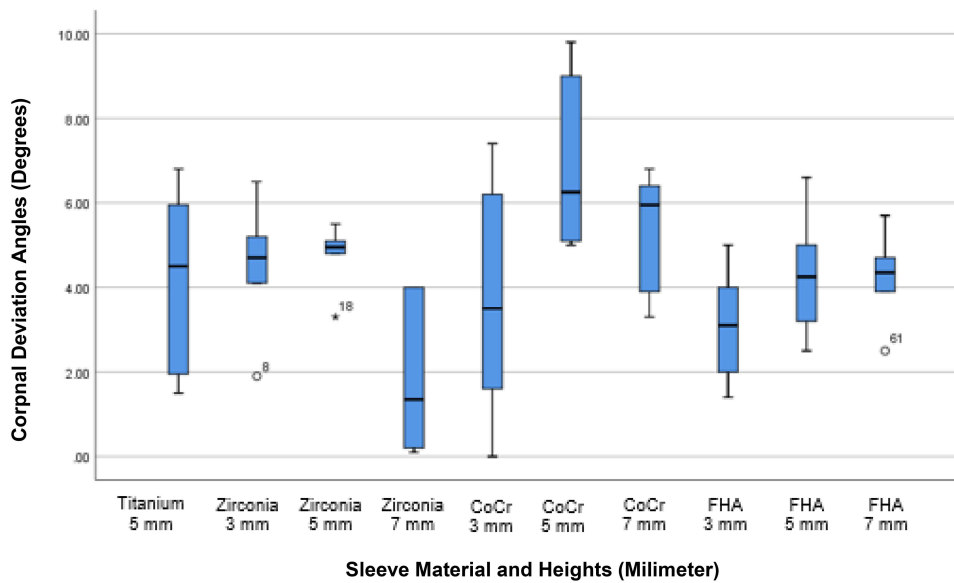


Figure 3 Mean coronal deviation by material and sleeve height (degrees).

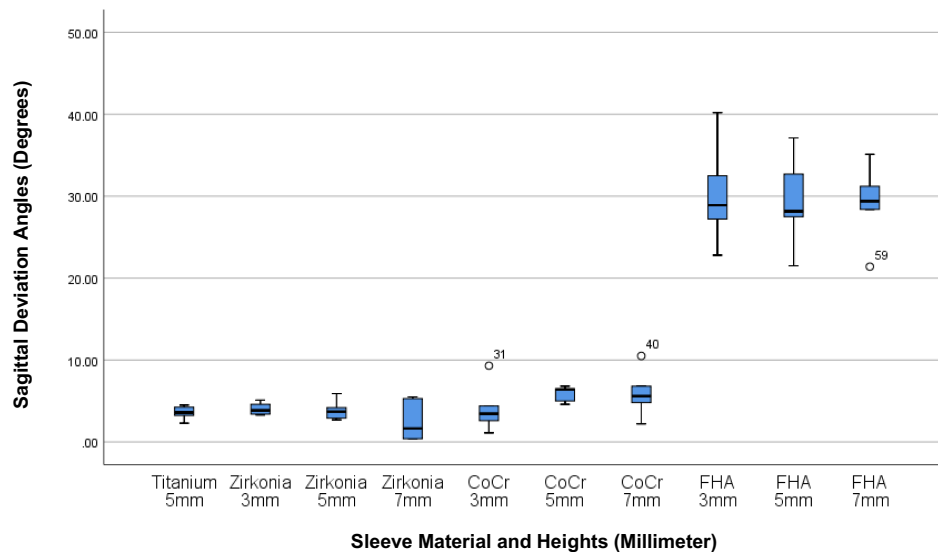


Figure 4 Mean sagittal deviation by material and sleeve height (degrees).

Although CoCr exhibits high stiffness, its greater deviation may result from higher sleeve bur friction, minor manufacturing inaccuracies, or surface roughness that reduces guidance precision. The limited sample size may also have contributed to the variability in these findings.

This study demonstrates that static guided endodontic access with precision sleeves markedly improves drilling accuracy in simulated PCO cases, and that sleeve design parameters modulate this effect. All guided protocols (titanium, CoCr, and zirconia sleeves) produced significantly lower sagittal deviations compared to freehand access ($p < 0.001$).^{6,14} This finding is consistent with clinical findings that guided endodontics yields superior outcomes to conventional methods.^{6,14} The only occasional difference in coronal deviation was that 7 mm zirconia guidance yielded a statistically smaller angle than freehand. The reported 1–3° deviation range in previous studies refers to guided access techniques, which are consistent with our guided groups.^{6,11}

The higher deviation observed in the freehand group ($\sim 30^\circ$) represents the expected inaccuracy of manual drilling and was included for comparison, not as part of the guided performance range. For instance, Li et al found a mean angular deviation of $\sim 1.75^\circ$ with static guides in PCO teeth (versus significantly larger freehand values).¹¹ Likewise, guided treatment cases had no perforations in Torres et al's clinical trial, whereas freehand had multiple, yielding a significant advantage for guidance.⁶ Our results reinforce that guided access is highly predictable and mitigates the risk of canal miss or perforation in calcified cases.

Sleeve height also affected performance, though to a lesser extent. The 7 mm sleeves (longest) tended to yield lower deviations than 3 mm sleeves. This result aligns with implant studies, which show that increasing sleeve length (thus reducing free drill distance) improves stability.³² In static implant surgery, El Kholy et al found that longer sleeves (or reduced drilling distance) significantly reduced lateral deviations.³² Similarly, our longer endodontic sleeves provided more guidance than shorter ones, though even the shortest (3 mm) sleeves offered much better accuracy than freehand. This finding indicates diminishing returns: once the guide controls the drill sufficiently, further length adds only marginal benefit. Clinically, using a taller sleeve (when mouth opening permits) is advisable. Notably, the 7 mm zirconia sleeve performed best overall; however, the 5 mm titanium control performed similarly to the 7 mm CoCr, suggesting that material stiffness can partly compensate for a shorter height. The improvements in accuracy we observed have clear clinical implications. Even a few degrees of deviation can mean missing a calcified canal or perforating.

Guided access with an optimal sleeve thus significantly increases the chance of precisely hitting the canal orifice. This finding is consistent with the umbrella review conclusion that guided techniques improve endodontic success metrics.¹⁴ The findings support the robustness of guided access designs and indicate that clinicians may prioritize ergonomic and clinical considerations such as visibility and irrigation when selecting sleeve parameters, without compromising accuracy.^{15,20,25,26,33,34} In terms of patient outcomes, fewer procedural errors likely translate to fewer retreatments. The cost-effectiveness of custom guides remains a concern, but utilizing in-house 3D printing and unconventional materials, such as zirconia (which can be milled or printed as a ceramic), may make this approach more accessible.

Limitations of this *in vitro* study include the use of uniform resin models without anatomical variability and controlled drilling performed by an experienced operator. Clinical factors such as limited mouth opening, patient movement, and intraoral constraints were not simulated in this study. Although these limitations exist, the significant differences observed ($p < 0.001$) indicate the robustness of the results. Only angular deviations were measured; future studies should also evaluate linear and volumetric errors. Future studies should include randomized clinical trials on calcified molars, evaluate preparation time and cost-effectiveness, and compare sleeved and sleeveless systems to validate clinical applicability and optimize accuracy, stability, and efficiency in guided endodontics.

Conclusion

Custom sleeves and static guides provide precise endodontic access; they greatly enhance endodontic access accuracy in calcified canals. All guided methods (Chrome-Cobalt or Zirconia sleeves) dramatically reduced deviation compared to freehand ($p < 0.001$). Longer sleeves (7 mm) and rigid materials (zirconia) yielded the least drill-path error, particularly in challenging PCO scenarios. These results support the potential for the clinical adoption of optimized custom sleeve SGEA designs and suggest clinical benefits, including improved accuracy and reduced iatrogenic risk in guided endodontic access, preservation of dentin structure, and enhanced predictability of treatment in complex or calcified canal cases.

Data Sharing Statement

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Ethics Approval and Consent to Participate

The protocol was approved by the Institutional Review Board of Research Ethics Committee of Padjadjaran University (Nomor: 194/UN6.KEP/EC/2025) and followed the Declaration of Helsinki. Patients consented to the use of their extracted teeth for research.

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Disclosure

The authors report no conflicts of interest in this work.

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