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Accuracy of endodontic access guides printed by a cost-efficient 3D printer (An In-Vitro Study)

Islam Nabeel Yusuf Sharaf[1,2], Mohamed Mohamed Elashiry[3], Shehabeldin Mohamed Saber[1,4,5]

Aim: This study evaluated the precision and trueness of endodontic access guides fabricated using a cost-effective desktop LCD 3D printer compared to a higher-cost SLA printer for guided endodontics.
Materials and methods: Thirty-two root canals from Nissin typodont teeth were divided into two groups: LCD and SLA. Virtual planning was performed, and endodontic guides were fabricated using both 3D printing technologies. Pre-operative and post-operative cone beam tomography (CBCT) scans were taken, and the linear deviation between the planned and actual access paths was measured at two axial levels: the occlusal entry point and the canal orifice. Statistical analyses were conducted using independent samples t-test at $\alpha = 0.05$.
Results: At the occlusal entry point, the SLA printer demonstrated significantly higher accuracy with lower linear deviations compared to the LCD printer ($p < 0.05$). However, at the canal orifice level, no significant difference in deviation was observed between the two groups. Both 3D printing technologies successfully detected all root canals without perforations, showing comparable precision at the orifice level.
Conclusion: Although the SLA printer exhibited better accuracy at the occlusal level, the cost-effective LCD printer provided comparable results at the orifice level. These findings suggest that LCD 3D printers are a viable option for guided endodontics; they offer a cost-efficient solution for in-office use with proper planning and template design.

Keywords: Endodontic guide, static guide, calcified canals

1. Department of Endodontics, Faculty of Dentistry, The British University in Egypt, Cairo, Egypt.
2. Department of Oral Health and Dental Services, Primary Care, Ministry of health, Government Hospitals, Manama, kingdom of Bahrain.
3. Augusta University Dental College of Georgia: Augusta, GA, USA
4. Department of Endodontics, Ain Shams University, Cairo, Egypt.
5. Centre for Innovative Dental Sciences (CIDS), Faculty of Dentistry, The British University in Egypt (BUE), Egypt.

Corresponding author: Shehabeldin Mohamed Saber, email: Shehabeldin.saber@bue.edu.eg

Introduction

The most important goal of root canal treatment is to disinfect the pulp space. [1,2] This becomes challenging with pulp calcifications, which can cause errors or prevent proper shaping and cleaning. [3,4] Pulpal calcifications generally progress in a corono-apical direction. [5] Access cavity preparation is crucial in highly-calcified teeth, which are at higher risk of perforation during access or locating the canal orifice. [6] Managing calcified pulp spaces is classified as "high difficulty" by the American Association of Endodontics and the Canadian Academy of Endodontics. [7]

Guided endodontics combines cone-beam computed tomography (CBCT) with intraoral scanning to create custom-made stents that help reach pulp spaces safely in highly-calcified teeth. This technique requires less skill and fewer tools in accessing calcified pulp spaces. [8–10] Guided endodontics is more predictable and conserves more tooth structure (~5 times) than conventional access methods on a calcified 3D-printed tooth. [11] However, its use is limited by technical errors [12] and high cost.

Different 3D printing methods have been employed in dentistry, including stereolithography (SLA), direct light processing (DLP), and liquid crystal displays (LCD). These methods are all based on the vat photopolymerization technique a 3D printing process where a liquid light-curable resin monomer in a reservoir (vat) is selectively cured or hardened by a light source (usually ultraviolet light). Nevertheless, their prices differ significantly. Cost-effective desktop 3D printers were found to be as accurate as dental laboratory 3D printers in printing implant surgical guides. [13] However, few studies have evaluated such printers in guided endodontics. Accordingly, the objective of the present *in-vitro* study was to compare the precision and trueness of the printed products produced by two 3D printing methods.

From a metrological point of view, precision refers to the ability of a 3D printer to consistently produce the same result over multiple attempts. It measures the reliability and repeatability of the output. In other words, if a machine is precise, it will generate the same or very similar results each time it completes a task, even if those results may not exactly match the intended target. Precision is critical in ensuring uniformity, but it does not necessarily mean the result is accurate. The result is simply consistent. Trueness, on the other hand, is a component of accuracy that evaluates how close the output of a 3D printer is to the intended result. It measures the deviation between the actual produced object and the ideal design. High trueness indicates that the printer can closely match the exact specifications or target. Unlike precision, trueness is about getting the correct result in relation to the desired goal, regardless of whether the result is consistently repeatable.[14] Ideally, a high-quality 3D printer should exhibit both high precision and high trueness, ensuring it consistently and accurately produces objects that match the planned design. [15] Based on these criteria, the null hypothesis tested was that there is no significant difference in precision and trueness between guided endodontic templates produced by a higher-cost SLA technology-based printer and a cost-effective desktop LCD 3D printer.

Materials and methods

Ethical approval, sample size calculation and grouping

The study did not include any human or animal subjects. The protocol was approved by The British University in Egypt Faculty of Dentistry Research Ethics Committee (number 22-036). A power analysis was conducted to ensure sufficient statistical power for testing the null hypothesis. With an alpha level of 0.05, a beta of 0.02 (resulting in 80% power), and an effect size (f) of 1.033 based on the results of Su et al. [16], the minimum required sample size was found to be 32 teeth (16 per group). Sample size calculation was performed using G*Power version 3.1.9.7 (Heinrich-Heine-University, Düsseldorf, Germany). [17]

The teeth were divided into two groups: LCD and SLA. In the LCD group, the Halot-one printer (Shenzhen Creality 3D Technology Co., Ltd, China) was used to represent cost-efficient printers. In the SLA group, the Form2 printer (model FLGPGR04, Formlabs, Somerville, MA, USA) was used. At the time of the study, these printers were priced at approximately $350 and $3500, respectively.

Macroscopic processing

Thirty-two canals from root canals-containing Nissin typodont acrylic teeth were used for the study. These artificial teeth were designed to mimic the natural anatomy of human teeth. The collected teeth were fitted alternately into a Typodont study model (Nissin typodont study model, Nissin Dental Products, Inc., Kyoto, Japan). Fitting was performed in accordance with the anatomical position of each tooth to simulate a realistic clinical environment. This alignment ensured that the root canals were positioned as they would be in a typical dental arch, to enable a more accurate assessment of guided endodontic access techniques.

Pre-operative 3D imaging and surface scanning

Pre-operative CBCT scans with the parameters of 150 µm voxel size, 110 kV, 30 mA, and a 12×8 cm field-of-view were performed using the Planmeca Oy system (FI-00880, Helsinki, Finland). The acquired data were saved in Digital Imaging and Communication in Medicine (DICOM) format. These CBCT images were used to identify the visible root canal and plan the most conservative access path to the root canal system. [11] In addition, the models were scanned with a surface scanner (Medit T310 Scanner, Medit Corp., Seoul, Korea). The surface scan data were saved in the surface tessellation language (STL file format). The STL files enabled integration of surface details with the CBCT data for further analysis and planning.

Virtual planning of static endodontic guide

Virtual planning for static endodontic guide was performed using the method described by Kelliny (2023) [18], using the Blue-Sky Plan software (Blue Sky Bio, Chicago, IL, USA). The STL file acquired from the surface scan and DICOM file acquired from CBCT scan were imported, superimposed and aligned by matching the outlines of the teeth in the Blue Sky Plan software. After alignment, the “endo-mode” tab was selected in the program and was used to identify the location of the initial entry point through the remaining canal.

The dimensions of the endodontic access bur (molar kit order #18051 for endodontic exploration, EG7 low-speed bur, SS White Dental, Lakewood, NJ, USA) were used for virtual access cavity planning. The “add implant” tab was used to create a virtual image of a bur with 1.34 mm diameter. This virtual image was positioned at the top of the visible portion of the root canal system, within the parameters of a conservative endodontic access cavity.

Templates were designed with a 3.05 mm inner diameter for the sleeve guide hole, and a sleeve height of 7.5 mm to accommodate the metal sleeve (JDBGP Pin Sleeve, JDentalCare, Modena, Italy). Once the plan was determined to be satisfactory, the “guide panel” tab was used to generate the guide design. Depending on the tooth, the guide was extended across the midline, or to

2-3 teeth adjacent teeth mesially and distally to ensure anterior-posterior and bucco-lingual tilt control. [19] Windows were incorporated into the design to enable visual confirmation of the fit. The final STL file of the stent was exported for printing with the two 3D printers.

Computer-aided manufacturing

The STL file of the template was exported from the planning software and processed using the software for the selected 3D printer. This software was used to prepare the file for 3D printing by adding supports and slicing the object into 25 µm layers. both printers were calibrated following manufacture instruction to ensure the best performance during printing process.

Printing was performed by an independent commercial laboratory (Digital Dental Academy, Cairo, Egypt) for both printer's and surgical guide resin was used at the highest available resolution for each printer. The layer thickness was set at 0.025 mm for both printers to ensure the production of identical stents.

Post-processing and removal of the support materials were performed according to the criteria provided by the resin manufacturer to avoid dimensional changes. [20] After the supports were removed, all templates were washed with 90% alcohol then post-cured using LED light curing device. Finally, the fit of each endodontic guide on the study model was visually checked, using windows space to confirm a precise fit.

Test procedures on embedded teeth

Initially, the sleeves were integrated into the guide hole of the template. The typodont tooth was then accessed using the bur at 10,000 revolutions/min. A low-speed handpiece was used to drive the bur through the sleeve of the template, in a pecking motion, until the back of the bur reached the mechanical stop of the metal sleeve. During this process, the bur was cleaned with gauze, and irrigation was performed with normal saline every 2 mm of drilling.

The aforementioned procedures were repeated 16 times on different typodont teeth with artificial canals. The procedures were performed by the same endodontic resident. In each case, the bur was guided through the sleeve to gain access to the orifice of the root canal. The mechanical stop of the sleeve confirmed that the bur had reached the planned depth.

After the guided access cavity preparation, each canal was checked with a size 10 K-file (Dentsply Sirona) to check for accessibility. The procedure was considered successful when the K-file could reach the root canal through the guided access cavity preparation without any resistance. Otherwise, the canal was considered inaccessible. The workflow of guided endodontics procedure is summarized in (**Error! Reference source not found.**).

Post-operative 3D imaging and analysis of drill path

After accessing all 32 canals, the typodont teeth underwent CBCT scanning using the same parameters as the pre-operative scans. Each post-operative scan was imported as a DICOM file into the 3D slicer imaging platform (v 4.8.1, www.slicer.org). [21] Segmentation of the typodont study model was performed using segment editor tab, where the DICOM data was processed. Semi-automated segmentation and manual refinement with a threshold range of 863.24 and 2475 were applied to accurately identify the artificial teeth with canals outlines. A 3D model was created using the "show 3D" function. After segmentation was completed, the data was exported as an STL file. [22]

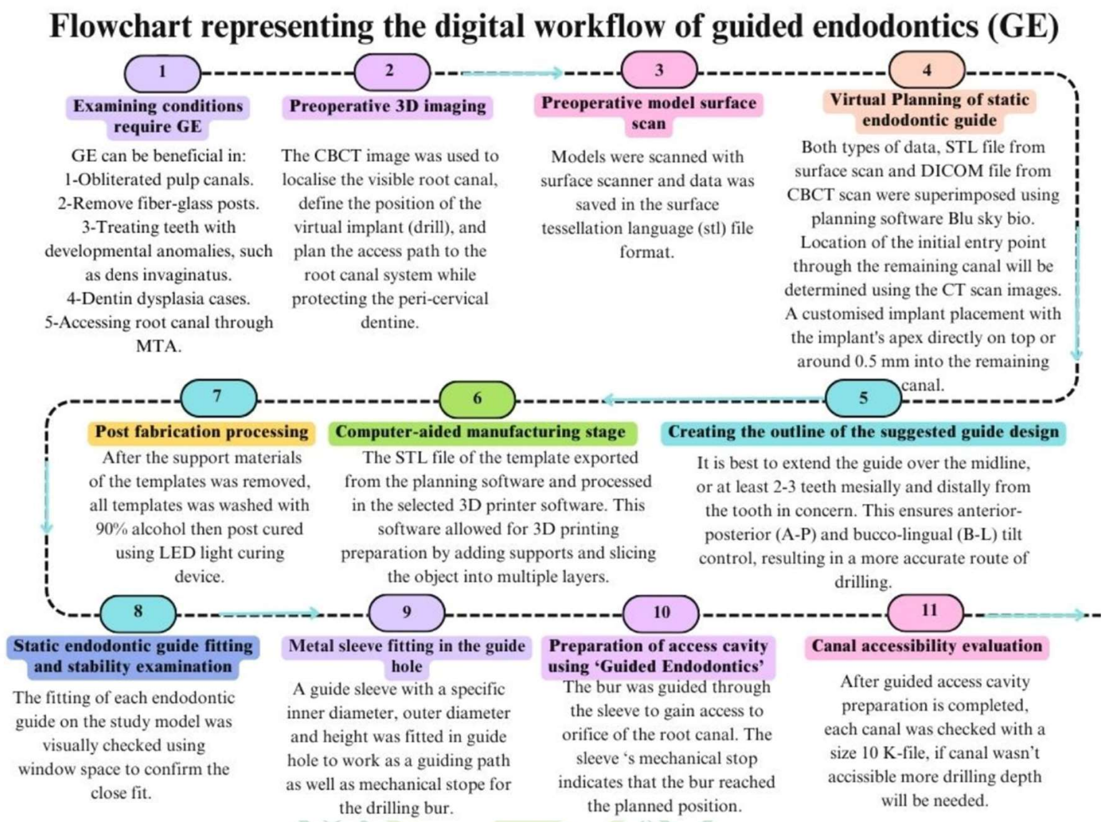

Figure 1: Flowchart depicting the workflow for creating guided endodontic templates and the *in vitro* evaluation procedures, including imaging, virtual planning, template design, manufacturing, and canal accessibility evaluation.

All pre-operative guide planning files and post-operative segmented STL files for each group were imported and aligned in the Blu Sky Bio planning software. Alignment was performed by matching the outlines of the teeth. Multiple surface CT points within each STL file were used for the superimposition method. After aligning both scans, the virtual bur from the planning stage was placed over the access cavity of the post-operative scan. The superimposed datasets were sectioned axially at the occlusal entry point and the orifice level.

Coronal entry point deviation was defined as the distance between the bases of the virtual bur and the actual bur. Apical or orifice level deviation was defined as the distance between the tips of the virtual bur and actual bur. The linear deviation was calculated in millimeters based on the center of the circle in cross section (**Error! Reference source not found.**) (**Error! Reference source not found.**) (**Error! Reference source not found.**).

Data collection and statistical analysis

Data obtained from the practical measurements were expressed as continuous variables. Descriptive statistics were presented as mean and standard deviation for normally distributed data. The Shapiro-Wilk test and the modified Levene's test were used respectively to determine the normality and homoscedasticity assumptions of the data. If these assumptions were not violated, comparisons between the two groups were conducted using an independent samples t-test. A p-value of less than 0.05 was considered statistically significant. In addition, 95% confidence intervals were calculated for each parameter. Statistical analyses were performed using the Jamovi software (Version 2.4; https://www.jamovi.org). [23]

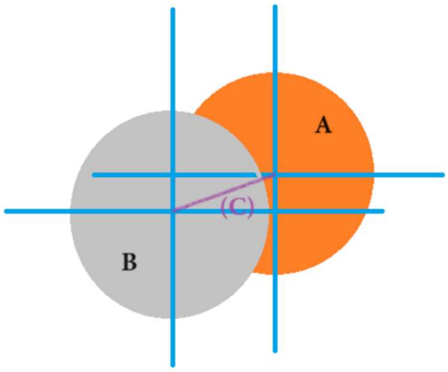

Figure 2: Illustration demonstrating the calculation of the deviation between the planned pathway (A) and the drilled pathway (B) in a cross-sectional view. The linear deviation (C) is represented as the distance between the centers of the two circles. This value represents the difference between the intended and actual drill positions.

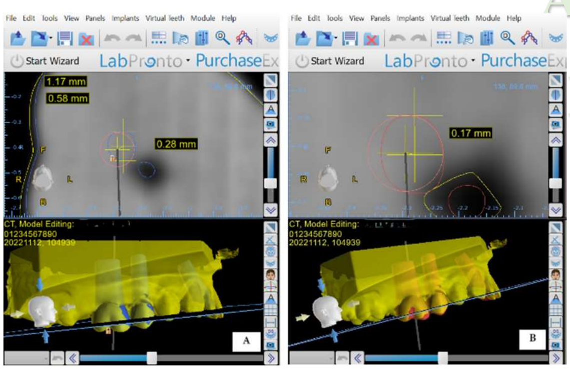

Figure 3: A representative example of the linear deviation at the occlusal entry point. Image (A) demonstrates the deviation for the LCD-printed endodontic guide. Image (B) shows the deviation for the SLA-printed guide. The measurements reflect the accuracy differences between the two 3D printing technologies at the entry point.

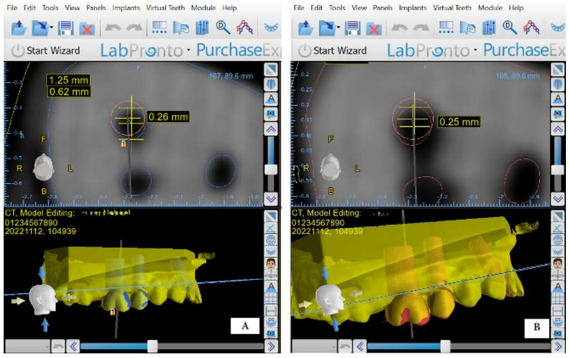

Figure 4: A representative example of the linear deviation at the orifice level. Image (A) demonstrates the deviation for the LCD-printed endodontic guide. Image (B) shows the deviation for the SLA-printed guide. These measurements reflect the differences in accuracy at the orifice level between the two 3D printing technologies.

Results

Both LCD-printed and SLA-printed endodontic guides successfully detected all root canals in their respective groups of 16 canals. There were no instances of root perforation in either group. The linear deviation of the guided access was measured at two axial levels: the occlusal entry level and the canal orifice level. Trueness was reported as the mean axial deviation, while precision was expressed as the standard deviation. The results for both groups are summarized in (Table 1) and illustrated graphically in (**Error! Reference source not found.**).

Both the entry point and orifice level linear deviation data were parametric and followed a normal distribution. A significant effect of the printer technology type was observed on the entry point linear deviation, with the SLA printer showing a statistically significant advantage over the LCD printer ($p < 0.05$) at the occlusal level. However, no significant effect of printer technology was found on the orifice level linear deviation. This finding indicates that both printers performed similarly at this axial level.

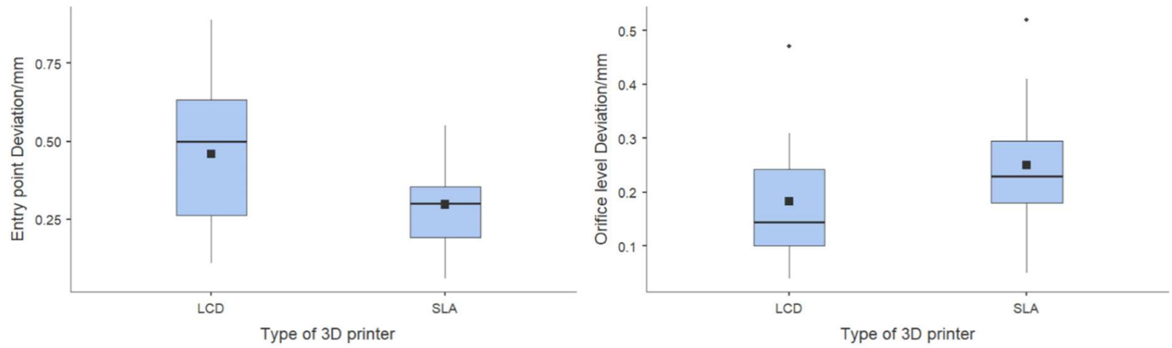

Figure 5: Box and whisker plots demonstrating the axial deviation at both the entry point and orifice level for the LCD and SLA 3D printers. The left plot shows the deviation at the entry point, where the LCD printer exhibits a higher deviation compared to the SLA printer. The right plot presents the deviation at the orifice level, with both printers showing relatively similar deviations, though the LCD printer has slightly larger variability. The black square within each box represents the mean deviation, and the whiskers indicate the range of values. The outliers are displayed as individual points outside the whiskers. These plots illustrate the trueness (accuracy) and precision differences between the two 3D printing technologies at different axial levels.

Table 1: Statistical results of entry point and orifice level linear deviation

Level	**Type of 3D printer (n)**	**Mean (SD)**	**Minimum discrepancy**	**Maximum discrepancy**	**Difference (95% CI)**	**P-value**
Occlusal entry point linear Deviation/mm	LCD (n=16)	0.45 (0.23)	0.11	0.89	0.16 (0.01, 0.30)	**0.029***
	SLA (n=16)	0.29 (0.14)	0.06	0.55		
Orifice level linear Deviation/mm	LCD (n=16)	0.18 (0.10)	0.04	0.47	-0.06 (-0.15,0.01)	**0.110***
	SLA (n=16)	0.25 (0.12)	0.05	0.52		

Abbreviation: CI (confidence level); LCD (liquid crystal display); SD (standard deviation); SLA (stereolithography)
*** *S*tatistically significant (*P* < 0.05)**

Discussion

Despite its benefits, the cost-versus-benefit analysis of guided endodontics continues to challenge its justification for regular use in routine root canal treatment. Conversely, guided endodontics significantly reduces the risk of perforations in highly-calcified teeth. [24,25] This advantage, coupled with shorter chair-side times, can help justify its high cost. Efforts to improve the cost-efficiency of guided endodontics focus on evaluating different 3D printing technologies. This study follows that path by comparing a higher-cost SLA printer with a low-cost desktop LCD printer. There was a significant difference in precision and trueness at the occlusal entry level, with the SLA printer demonstrating better performance compared to the cost-effective LCD printer. However, there was no significant difference observed at the orifice level. Taken together, the findings warranted partial rejection of the null hypothesis that "there is no significant difference in precision and trueness between guided endodontic templates produced by a higher-cost SLA technology-based printer and a cost-effective desktop LCD 3D printer".

The study design was carefully structured to reduce confounding factors. Typodont artificial teeth with root canal spaces were selected because their Hounsfield unit, a measurement of radiodensity, is similar to that of natural dentin. This similarity enabled clear visualization in CBCT scans to ensure accurate detection of anatomical structures. [26] Natural teeth were not used because of the difficulty in standardizing canal position and angulation. This challenge is particularly significant in molar teeth which exhibit wide anatomical variations. [27–29] To minimize fitting-related errors, guide windows were incorporated during template design to provide visual assessment. [30] Metal sleeves of 8 mm length were used to reduce lateral deviations and increase stability, thereby improving precision. [31] The study also employed a smaller diameter bur (1.34 mm) to enhance accuracy by using a more conservative technique.

At the occlusal level, a statistically significant difference was observed between the two groups when comparing the linear axial deviations; the SLA printer demonstrated an advantage over the LCD 3D printer. However, no significant difference in linear axial deviation was identified for the two printers at the orifice level. Despite the occlusal deviation, it did not interfere with the primary goal of predictably locating the canal while avoiding iatrogenic perforations. Furthermore, recent stress-analysis studies indicate that reducing the access cavity size from conservative to ultra-conservative access is not advantageous as long as the marginal ridges remain intact. [32] Therefore, the slight difference in the amount of enamel and dentin removed due to minimal occlusal deviation is unlikely to adversely affect tooth survival.

Providing direct access in the coronal third c an reduce the risk of perforations, false route s, and transferred canals[33] which was achievable using both types of guided templates. Generally, minimally invasive cavities tend to bend endodontic instruments, causing stress on the canal. This can result in iatrogenic mishaps, such fractures, or steps[34] However, by means of static guide, this did not take place since the access is direct, linear, and parallel to the axis of the canal. The loss of dental tissue is clearly lower in more conservative access cavities than in traditional access cavity. It has been demonstrated that fracture resistance in anterior teeth is unrelated to the kind of endodontic access, in contract, posterior teeth, there are some differences. Some research suggest that endodontic access does not affect tooth stiffness provided marginal ridges are retained.

Compared with the promising results reported by Zehnder *et al.* (2016) and Connert *et al.* (2017) [35,36], the present study showed slightly lower accuracy for the LCD-printed guide at the occlusal entry level, with an average linear deviation of 0.45 mm. However, the current study demonstrated comparable accuracy to both studies at the orifice level. The difference at the occlusal level may be attributed to a wider gap (≈ 0.2 mm) between the tapered drilling bur and the sleeve during the initial drilling stage. This deviation remains acceptable, considering that the trade-off was limited to the occlusal level. It is also important to note that Zhender *et al*. (2016) [35] employed a more expensive PolyJet 3D printer (Objet Eden 260 V, Material: MED610, Stratasys Ltd., Minneapolis, MN, USA) with an average price of US $19,800. Connert *el al.* (2017) [36], on the other hand, optimized their approach to a 'micro-guided' technique that improved the snugness of the guide. Koch *et al.* (2018) [13] reported larger deviations on both levels compared to this study. However, they still considered the results acceptable and concluded that exploring cost-effective 3D printers for guided endodontics is justified.

Apart from these comparisons, Su *et al.* (2021) [16] reported significantly higher deviations at the orifice level (≈ 0.4 mm), even though they used an SLA printer (Form 2, Material: FLGPGR04, Formlabs). This discrepancy may be attributed to the differences in methodology, including their use of natural teeth and a thicker printing layer (0.05 mm compared to 0.025 in the present study).

The results of this study suggest that the LCD technology used to produce endodontic guides at a lower cost would not adversely affect the treatment of highly-calcified teeth. The results also suggest that a snug fit between the bur and its sleeve (i.e., minimal sleeve gap) probably plays a more critical role than the choice of 3D printer, provided that there is proper planning and execution. This may explain why guided endodontics shows more favorable axial deviation values compared to the similar techniques in implantology. [37] In guided endodontics, the tighter fit between the bur and sleeve improves precision. In addition, guided endodontics uses a single bur throughout the procedure, and the sleeve is supported by hard dental structure. In contrast, the sleeve rests on resilient mucosa in implant placement. These factors probably account for the improved accuracy of templates used in guided endodontics.

These findings affirm previous that guided endodontics is a safe, simple, and predictable approach in locating highly-calcified canals. The demonstrated feasibility for using cost-efficient printers to fabricate templates may also encourage less experienced operators to adopt guided endodontics in routine practice, particularly in cases where iatrogenic complication poses a significant risk. [12] However, the study has limitations. Being an *in vitro* study on artificial teeth without canal obliteration, the results cannot account for the resistance posed by calcific tissue on the drilling bur. Therefore, high-quality clinical studies are necessary to examine this aspect. In addition, limitations inherent to guided endodontics should be considered. A significant limitation is that the static micro-endodontic template is only suitable for the straight portions of root canals. [38] This design constraint means that while guided endodontics provides excellent precision and control in the early stages of canal access, it becomes less effective when navigating the complex anatomy of curved root canals, particularly in molar teeth. Accessing these curved regions still poses challenges for clinicians, as the static nature of the template prevents it from adapting to the canal curvature. As a result, alternative techniques or further advancements in guided endodontics technology are required to improve access and precision in these more complex cases.

A suggested solution for the limited accessibility in molar region, include the sleeveless guide system which relies on rails and cylinders attached to the handpiece to guide the direction. This technique requires less room above the occlusal surface and offers better visibility compared to sleeve templates, making it suitable for molar areas with limited vertical space. [39]As regard the ongoing development in guided endodontics, dynamic navigation systems (DNS) offer equivalent precision to static templates and allows for real-time changes to access cavity direction. However, better hand-eye coordination and technical skill are required to operate DNS, and the higher cost is regarded as an additional barrier. One advantage over static navigation is that the template production stage is omitted, allowing patients in extreme pain to be treated promptly.

Conclusion

Within the limitations of this study, cost-effective 3D-printers may provide sufficient accuracy for access cavity preparation in guided endodontics. Although linear deviations were significantly higher at the occlusal entry level for the cost-effective LCD 3D printers compared to the SLA printer, both printers produced comparable precision at the orifice level.

These findings suggest that clinicians can confidently implement guided endodontics in-office using more affordable 3D printers, provided that careful attention is given to template design and planning. This may help expand the accessibility of guided endodontics without compromising treatment outcomes, making it a viable option for broader clinical use.

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Data availability

Data available upon reasonable request from the corresponding author.

Ethics approval and consent to participate

This study had an ethical clearance from the research ethics committee at the Faculty of Dentistry, the British University in Egypt, with the approval number (FD BUE REC 22-036) as it did not include any human or animal subjects.

Competing interests

None

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