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RESEARCH

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The effect of storage conditions and duration on dimensional stability of 3D-printed endoguides

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Abstract

Background This study evaluated the dimensional stability and angular deviations of 3D-printed endodontic guides under varying storage conditions (wet vs. dry, dark vs. daylight) and durations (7 vs. 14 days).

Methods Endodontic guides for the localization of obliterated canals were designed using BlueSkyPlan software (BlueSky Bio, IL, USA) and printed with Biomed Clear Resin V2 (Formlabs Inc., Somerville, USA) via SLA technology. A total of 40 endodontic guides were fabricated and divided into four groups ($n=10$), each subjected to either light or dark storage conditions for durations of 7 or 14 days. Dimensional stability was assessed using root mean square (RMS) and angular deviations in Geomagic Design X (Oqton, USA). Statistical analyses were performed using IBM SPSS v29 with independent samples and paired t-tests ($p=0.05$).

Results Guides stored in dry conditions had lower RMS (0.052 ± 0.013) and angular deviations (0.29 ± 0.11) than wet conditions (RMS: 0.069 ± 0.028, $p=0.001$; angle: 0.36 ± 0.11, $p=0.008$). Angular deviations increased at 14 days ($p=0.003$). Daylight exposure increased RMS deviations at 14 days in dry conditions ($p=0.001$). Wet storage in dark conditions led to greater deviations at both time intervals($p<0.05$).

Conclusions Storage conditions and duration significantly affect the dimensional stability of 3D-printed endodontic guides. Wet storage and prolonged duration reduce accuracy. To maintain precision, guides should be used within 7 days and stored in dry, dark environments.

Clinical trial number Not applicable.

Keywords Dimensional stability, Endoguide, Storage conditions

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Introduction

The primary objectives of endodontic treatment are to gain access to the root canal system, perform chemomechanical disinfection, and establish a hermetic seal to promote apical healing [1, 2]. Proper preparation of the access cavity constitutes the initial and critical step for nonsurgical root canal therapy [3]. An inadequately prepared access cavity has the potential to alter the original orientation of the root canal, leading to unnecessary loss of tooth structure or perforation [2, 4]. Guided endodontics is an alternative to traditional access cavity preparation [5]. This technique demonstrates an accuracy rate exceeding 90%, and facilitates the creation of the canal path in accordance with the planned treatment, regardless of the operator's level of experience [6–8].

In a manner analogous to the 3D planning of dental implant positions within the jawbone, in endodontic treatments, the appropriate rotation, angle, and position of the bur during access cavity preparation can be virtually predefined. This method assists clinicians in achieving predictable and safe outcomes, minimising unnecessary tooth structure loss and improving treatment prognosis [9–11]. The successful application of guided endodontics in complex cases, such as the treatment of teeth with calcified canals and the removal of fiber posts, has been demonstrated in studies [12–14]. Despite the high success rates reported in the literature, there remains a paucity of data regarding the safety, limitations, and factors influencing the success of this technique [15]. It is therefore incumbent upon clinicians to remain cognizant of potential circumstances that could lead to failure and to take necessary precautions to prevent iatrogenic damage [16].

Accurate fabrication is a critical factor influencing the success of endoguides. Achieving proper guide preparation is possible through an appropriate design process and precise manufacturing techniques. An optimal design relies on high-resolution CBCT imaging and precise measurements, whereas high-accuracy manufacturing depends on the production technology and the type of material used [17]. Despite the absence of studies exclusively focusing on endodontic guides, an examination of studies involving endoguides reveals that researchers commonly utilise milled or 3D-printed acrylic materials for their fabrication [18]. Acrylic is a material known to absorb water, which can lead to dimensional instability influenced by environmental conditions [19]. This assertion is further substantiated by extant research in the field of dentistry, which has evaluated the accuracy of 3D-printed and milled acrylic materials [18, 20, 21].

In the contemporary context of the burgeoning utilisation of digital systems within dentistry, there has been a marked escalation in their integration into dental treatment modalities. However, there is a paucity of research addressing how an endoguide, produced using 3D printing technology—the most commonly used method for endoguide fabrication—should be stored from the time of production until its use in root canal therapy. The objective of this study is to evaluate the dimensional accuracy of endodontic guides fabricated via 3D printing technology under different storage conditions and durations from the time of production to their use in root canal therapy. The first hypothesis of the study is that the accuracy of endodontic guides will be affected by the storage duration, with prolonged durations leading to greater loss of accuracy. The null hypothesis suggests that storing the guides in either humid or dry environments and dark or light conditions may influence their accuracy.

Materials and methods

Study design and sample size calculation

This in vitro experimental study was designed to evaluate the effects of different storage conditions (wet vs. dry and dark vs. light) and durations (7 vs. 14 days) on the dimensional stability of 3D-printed endodontic guides. A total sample size of 40 guides ($n = 10$ per group) was determined based on previous studies in the literature that assessed dimensional deviations in 3D-printed dental materials, aiming to provide sufficient statistical power ($\beta = 0.80$) with an alpha level of 0.05 [12, 22].

Endoguides desing

A hole with a width of 0.7 mm was prepared on the guide designed to fit mandibular posterior teeth, and a 19 mm long rod was incorporated into the design to simulate the canal axis (Figs. 1 and 2). Endoguides were designed using BlueSkyPlan (Blue Sky Bio, IL, USA) and exported as STL files. These files were prepared for 3D printing using PreForm software (Formlabs Inc., Somerville, USA) with the following specifications and rationale:

Material selection

The guides were printed using Biomed Clear Resin V2 (Formlabs Inc., Somerville, USA).

3D printing process

The Endoguides were printed using a Form 3B + printer (Formlabs Inc., Somerville, USA) with the following settings:

- Layer Thickness: 50 microns (0.05 mm), balancing speed and resolution while ensuring dimensional accuracy for surgical fit.
- Print Orientation: The guides were printed in a horizontal orientation to minimize layer lines on critical surfaces, ensuring smooth interfaces with mucosal and bone structures. This configuration also

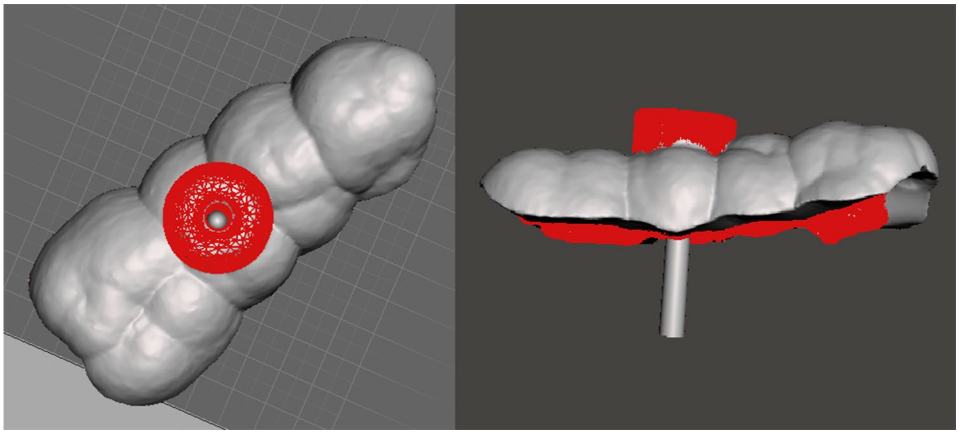

Fig. 1 Endoguide design STL format

Fig. 2 Angle deviation measurement

reduced peel forces during printing, as evidenced by the reduced warping in horizontal prints.

Support structure settings

Supports were generated automatically in PreForm software (Formlabs Inc., Somerville, USA) and refined manually to minimsurface blemishes on critical areas:

- Touchpoint Size: 0.3 mm, ensuring stability during the print while facilitating easy removal.
- post-processing.
- Support Density: 100%, balancing support strength and material usage.
- Raft Thickness: 1.5 mm, providing strong adhesion to the build platform.
- Model Elevation: Positioned 5 mm above the platform to optimize resin drainage and ensure clean prints.

Post-processing

Upon completion of printing, the Endoguides underwent the following post-processing steps:

1. Cleaning: Printed parts were washed in 99% isopropyl alcohol (IPA) using a Form Wash unit for 8 min, as prolonged exposure could lead to resin degradation and dimensional instability.
2. Drying: The parts were air-dried in a clean environment for 10 min to evaporate residual IPA.
3. Curing: Final curing was performed in a Form Cure unit (Formlabs Inc., Somerville, USA) at 60 °C for 30 min, as recommended by the manufacturer. This device is equipped with a high-intensity LED system that emits light at a wavelength of 405 nm and operates at a temperature of 60 °C. According to the manufacturer, the light intensity is approximately 39.5 mW/cm^2, a value that has been optimized to ensure complete polymerization of the resin. This ensured full polymerization and optimized the mechanical properties, enhancing the guides' strength and biocompatibility.

Subsequent to the production stage, one sample was scanned immediately after the completion of the post-processing procedure using a 3Shape E1 desktop scanner. This scanner has a laboratory-level accuracy of 10 microns, as defined by ISO 12,836. The Standard Tessellation Language (STL) file obtained was saved as the reference model. The samples were then divided into four groups: Wet-Light (WL), Wet-Dark (WD), Dry-Light (DL), and Dry-Dark (DD). A total of 40 samples were produced, with 10 samples in each group. The lighting conditions were set as normal interior room lighting and darkness, while the wetness conditions were defined as immersion in water at room temperature (23 °C) and dry storage. At the conclusion of the seventh and fourteenth days following the production stage, a scanning procedure was conducted on all samples using the 3Shape E1 desktop scanner. The resulting STL files were then saved in individual directories.

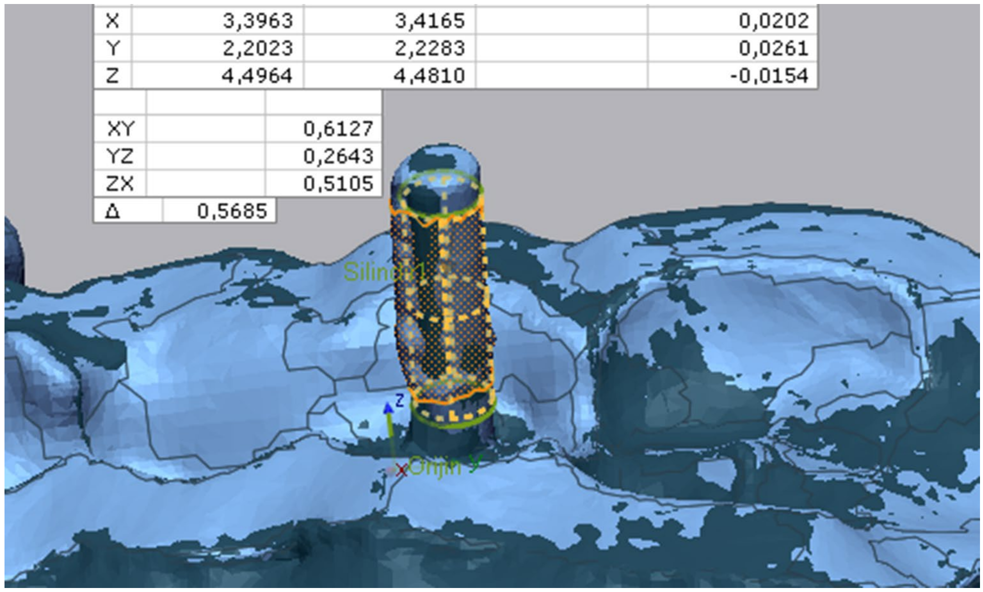

Fig. 3 Root mean square measurement

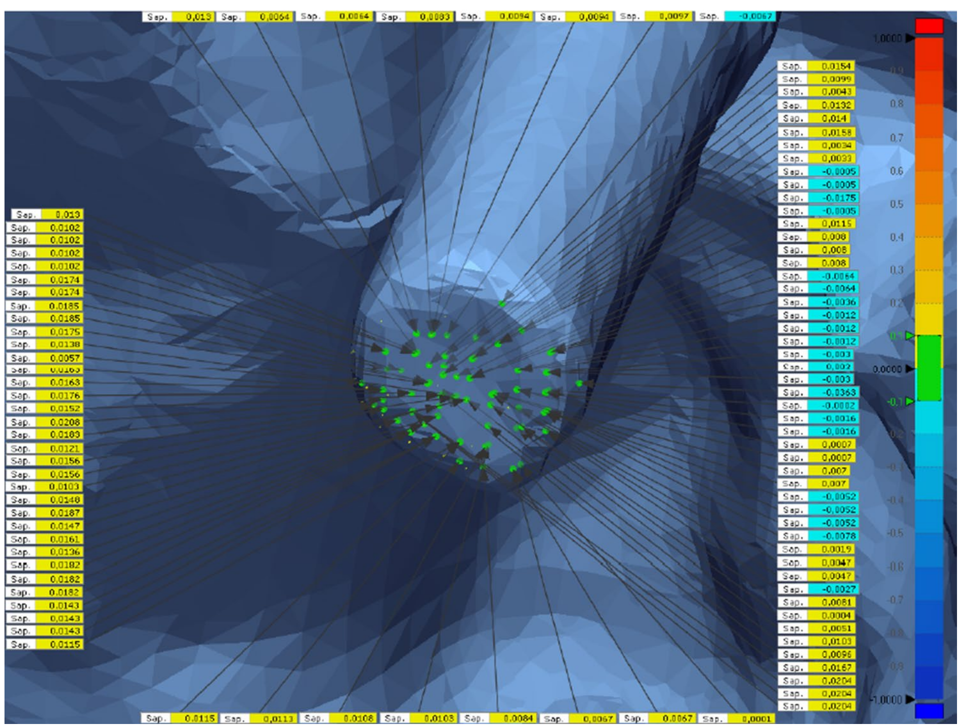

Fig. 4 Best fit alignment

Research on point-based measurements (e.g., marginal gap assessments) has indicated that evaluations based on a minimum of 20–25 points are adequate, with 50 points commonly regarded as reliable [23]. In accordance with these findings, 100 manually selected points were identified at the apical tip of the rod simulating the root canal. The mean square (RMS) deviation values of these points, as well as the angular deviation of the rod, were calculated using the best-fit alignment method in Geomagic Design X software (Figs. 3 and 4).

Statistical analysis

The data analysis was performed using IBM SPSS v29 software. The normality of the data distribution was assessed using both statistical and visual methods, including the Shapiro–Wilk test, the mean/SD ratio,

Table 1 Distribution of RMS and angle values of all materials according to dryness, darkness, and duration

	RMS	Angle
	Mean ± SD	***p* value**
Wet (*n* = 40)	0.069 ± 0.028	0.36 ± 0.11
Dry (*n* = 40)	0.052 ± 0.013	0.29 ± 0.11
p value*	**0.001**	**0.008**
Daylight (*n* = 40)	0.063 ± 0.026	0.33 ± 0.12
Dark (*n* = 40)	0.058 ± 0.019	0.31 ± 0.12
p value*	0.301	0.439
7 Days (*n* = 40)	0.056 ± 0.017	0.30 ± 0.10
14 Days (*n* = 40)	0.065 ± 0.027	0.35 ± 0.13
p value**	0.598	**0.003**

*Independent Samples T Test

**Paired Samples T Test

Table 2 Distribution of duration based on the darkness-dryness conditions for RMS and angle values of materials

RMS	7 Days	14 Days	*p* value*
	Mean ± SD	**Mean ± SD**	
Daylight-Dry	0.044 ± 0.008	0.065 ± 0.012	**0.001**
Daylight-Wet	0.069 ± 0.017	0.075 ± 0.045	0.709
Dark-Dry	0.048 ± 0.006	0.052 ± 0.016	0.568
Dark-Wet	0.063 ± 0.020	0.068 ± 0.024	0.451
Angle			
Daylight-Dry	0.32 ± 0.13	0.31 ± 0.15	0.901
Daylight-Wet	0.31 ± 0.11	0.39 ± 0.09	0.081
Dark-Dry	0.24 ± 0.08	0.27 ± 0.10	0.146
Dark-Wet	0.32 ± 0.09	0.41 ± 0.14	0.169

*Paired Samples T Test

Table 3 Distribution of dryness based on the darkness-duration conditions for RMS and angle values of materials

RMS	Dry	Wet	*p* value*
	Mean ± SD	**Mean ± SD**	
Daylight (7 Days)	0.044 ± 0.008	0.068 ± 0.017	**< 0.001**
Daylight (14 Days)	0.065 ± 0.012	0.075 ± 0.045	0.490
Dark (7 Days)	0.048 ± 0.006	0.063 ± 0.020	**0.043**
Dark (14 Days)	0.052 ± 0.016	0.068 ± 0.024	0.094
Angle			
Daylight (7 Days)	0.32 ± 0.13	0.31 ± 0.11	0.857
Daylight (14 Days)	0.31 ± 0.15	0.39 ± 0.09	0.163
Dark (7 Days)	0.24 ± 0.08	0.32 ± 0.09	**0.049**
Dark (14 Days)	0.27 ± 0.10	0.41 ± 0.14	**0.028**

*Independent Samples T Test

and kurtosis–skewness values as statistical criteria, as well as histograms and Q–Q plots as visual methods. Because the dataset met the 5/3 criterion, it was accepted as conforming to a normal distribution. Descriptive data for RMS and angle change values were presented as mean ± SD (Standard Deviation). For comparisons between groups, an independent samples t-test was used for dryness and darkness, and a paired samples t-test was used for duration. A Type I error rate of 5% was accepted for all analyses.

Results

In the overall comparisons (Table 1), dry conditions yielded significantly lower RMS values than wet conditions (0.052 ± 0.013 vs. 0.069 ± 0.028; $p = 0.001$) and showed a significantly lower angle (0.29 ± 0.11 vs. 0.36 ± 0.11; $p = 0.008$). Duration also affected angle values, with higher angle measurements at 14 days compared to 7 days (0.35 ± 0.13 vs. 0.30 ± 0.10; $p = 0.003$).

Subgroup analyses (Tables 2 and 3) indicated that, under daylight-dry conditions, RMS values were significantly higher at 14 days than at 7 days (0.065 ± 0.012 vs. 0.044 ± 0.008; $p = 0.001$). In addition, at 7 days daylight exposure, wet conditions had a significantly higher RMS than dry conditions (0.068 ± 0.017 vs. 0.044 ± 0.008; $p < 0.001$). Under dark conditions, at 7 days, RMS was significantly higher in wet compared to dry conditions (0.063 ± 0.020 vs. 0.048 ± 0.006; $p = 0.043$). Regarding angle measurements, under dark conditions, wet conditions resulted in significantly higher angles than dry conditions at both 7 days (0.32 ± 0.09 vs. 0.24 ± 0.08; $p = 0.049$) and 14 days (0.41 ± 0.14 vs. 0.27 ± 0.10; $p = 0.028$).

Discussion

The existing literature has evaluated the storage conditions and durations of acrylic-based materials, such as surgical guides and occlusal splints fabricated using 3D printing technology. These studies have investigated the effects of factors such as temperature [24], light exposure [25, 26], different storage conditions (wet or dry environments), various storage media (distilled water or saliva) [27], and different storage durations [21, 28] on the dimensional stability of these materials. However, to the best of our knowledge, no similar study has been conducted specifically for endoguides.

In this study, the utilisation of transparent resin for endoguides was driven by its ability to facilitate precise control over the fit between the supporting tooth and the guide, a feature that has led to its prominence in both clinical applications and in vitro studies [29]. The fabrication of the guides was undertaken using Biomed Clear Resin V2 (Formlabs, Somerville, USA), a material that has been selected for its exceptional biocompatibility, compliance with ISO 10,993 standards, and its robust mechanical properties, rendering it highly suitable for surgical applications [30]. This resin demonstrates excellent dimensional stability, a crucial factor in achieving the precision required for surgical implant guides. In addition, the literature supports the use of Biomed Clear Resin for its high accuracy, durability, and clarity, which enhance surgical visibility and minimise the risk of errors [31].

In the present study, a single stereolithography (SLA) printer was utilised in order to ensure the standardisation of the process. Research in the relevant literature has demonstrated that printers utilising SLA technology exhibit superior accuracy in comparison to other printer types [32, 33]. In order to eliminate any variability in production accuracy, all samples were fabricated using resin from the same bottle and positioned horizontally in the printer, as recommended in the literature [34]. Horizontal orientation was chosen to improve surface smoothness on load-bearing surfaces and critical interfaces, as per guidelines for surgical guide manufacturing.

Another factor thought to influence the accuracy of production protocols is layer thickness. In a study on surgical guides designed for implant placement, Panjnoush et al. [35] demonstrated that layer thickness could even impact angular deviations in holes. In this study, a layer thickness of 50 µm was selected during printing to produce endoguides with maximum accuracy.

Post-processing steps, including IPA washing and thermal curing, were performed in accordance with validated protocols in order to achieve maximum accuracy and ensure compliance with biocompatibility standards [36]. Dimensional accuracy and fit were verified against the digital CAD design using a digital caliper and a stereomicroscope. No significant deviations were noted, thus confirming the suitability of the production workflow for clinical use. This method provides a reproducible protocol for fabricating endoguides with high precision and biocompatibility.

In recent years, studies evaluating the accuracy of guided endodontics have been conducted, highlighting the reliability of this method [6, 37–39]. Zhang et al. [39] demonstrated in their study that minimising the diameter difference between the bur and the metal sleeve can provide a tighter bur-to-guide fit, leading to reduced angular deviations. However, they also noted that a smaller diameter difference may result in the bur rubbing against the inner surface of the metal sleeve at high speeds, causing slight vibrations and thermal deformation in the guide. Conversely, studies have shown that while tight contact between the bur and the guide may lead to heat generation, a loose fit could increase angular errors [37, 38]. To address this dilemma, an acrylic axis simulating the root canal was incorporated into the endoguide design in this study. At the conclusion of the designated experimental periods, measurements were obtained from the surface of the axis representing the root apex to evaluate dimensional changes and angular deviations in the guide. A notable distinction of the present study is its deviation from previous research, which primarily assessed the accuracy of the guide based on the amount of material removed. This discrepancy in evaluation methodologies precludes direct comparison of the results.

In the study by Alshaibani et al. [24], the dimensional stability of dental models fabricated using various resin and printer combinations was evaluated under three different temperature conditions: a cold environment (4 ± 1 °C), a hot and dry environment (50 ± 2 °C), and room temperature (25 ± 2 °C). The researchers reported that high temperatures had a detrimental effect on dimensional stability. In contrast, models stored at room temperature and low temperatures exhibited better dimensional stability compared to high temperatures. In line with these findings, the present study opted to store all groups at room temperature, thereby mitigating the potential for temperature-related effects on dimensional stability.

The photopolymerization properties of resin-based materials are initiated by the activation of photoinitiators within their chemical structure through the absorption of light energy. During the polymerisation process, the wavelength and intensity of the light determine the depth and effectiveness of the process. However, these materials may remain susceptible to reactions that could affect their stability when exposed to light post-polymerization [25, 26]. Yousef et al. [26] evaluated the effects of light exposure on the dimensional stability of 3D-printed dental models and reported that models stored in dark conditions maintained better dimensional stability after three months compared to those stored in light conditions. A comparable outcome was reported by Ntovas et al. [25] in their study on 3D-printed surgical guides, who recommended that surgical guides be stored in darkness until use. However, the extant literature also contains studies reporting contradictory findings on this subject.

In another study conducted over short durations of 1, 7, and 27 days, Antonopoulou et al. [21] compared the dimensional stability of occlusal devices stored in dry-light, wet-dark, and dry-dark conditions. The study found that the dry-light environment provided the best dimensional stability. In the present study, the RMS and angular deviation values in the dark storage groups (RMS = 0.058 ± 0.019, Angle = 0.31 ± 0.12) were lower than those in the light storage groups (RMS = 0.063 ± 0.026, Angle = 0.33 ± 0.12). However, these differences were not statistically significant. This discrepancy in results could be attributed to differences in experimental durations between studies. The samples in our study were stored for a period of 14 days, which is shorter than the three-month storage period that was utilised in previous studies. It can be hypothesised that prolonged light exposure over extended periods may exert a more significant effect on dimensional stability.

As endoguides produced for use in endodontic treatment do not require as long a storage period as dental models, a 14-day evaluation period was deemed sufficient when considering the laboratory-to-clinic workflow and treatment timeline. Consequently, the study was designed to assess two different durations: 7 and 14 days. It is hypothesised that over extended storage periods, the dimensional stability of 3D-printed resin endoguides may decrease. Dimensional instability has been identified as a critical factor that directly affects the clinical accuracy of 3D-printed endodontic guides. Minor deviations in the guides, which are designed to direct access to the root canal, may hinder the bur from following the planned trajectory, particularly during canal entry. These inaccuracies can lead to severe iatrogenic complications, including canal perforation, deviation from the original canal path, or unnecessary loss of dentinal structure. Furthermore, increased angular deviations may result in improper guidance, especially in the management of obliterated canals, thereby compromising treatment outcomes. Furthermore, inadequate adaptation between the guide and the supporting dental structures may lead to micro-movements and loss of stability during clinical use, increasing the risk of displacement during the procedure. Therefore, maintaining dimensional stability is essential not only for ensuring laboratory-level precision but also for guaranteeing procedural safety and clinical success during endodontic treatment [6–8].

As demonstrated by Knode et al. [28], the dimensional stability of 3D-printed resins decreases over time, with a time-dependent decline in stability at 7 and 21 weeks compared to baseline measurements. In the present study, a decline in dimensional stability was observed, as indicated by the RMS values, between the 7-day and 14-day periods. However, this difference was not found to be statistically significant ($p = 0.598$). Conversely, the angular deviation of the axis simulating the root canal exhibited a significant increase over these periods ($p = 0.003$). Consequently, it can be deduced that the utilisation of endoguides within the initial 7 days post-production is paramount in order to mitigate the risk of canal perforation.

Another potential storage condition that could influence the success of endoguides is the environment in which the guide is stored, whether wet or dry. Acrylic resins are hydrophilic materials capable of absorbing water molecules, and when stored in a wet environment, water molecules can penetrate the material, leading to swelling and dimensional changes [40, 41]. Our findings support this notion. Samples stored in a wet environment exhibited higher RMS values (RMS = 0.069 ± 0.028) and greater angular deviations in the canal axis (0.36 ± 0.11) compared to those stored in a dry environment (RMS = 0.052 ± 0.013, angular deviation = 0.29 ± 0.11).

The results of this study serve to confirm the hypotheses that were previously proposed. The dimensional accuracy of endodontic guides was found to be influenced by both the duration of storage and the storage conditions. This study is among a limited body of research on the dimensional stability of endodontic guides and is the first to comparatively evaluate the effects of both duration and storage environment. Although prior studies have examined the dimensional stability of 3D-printed dental materials, including occlusal splints, surgical guides, and diagnostic models, under various storage conditions, no study has yet comprehensively evaluated the dimensional accuracy of 3D-printed endodontic guides with respect to both storage duration and environmental conditions. The present study addresses this critical gap in the literature by being the first to systematically assess how humidity, light exposure, and time affect the precision of static endodontic guides. In contrast to previous research, which predominantly focused on surgical applications or general dental models, this study is specifically oriented towards endodontic use, where even minor deviations can potentially result in clinically significant consequences, such as canal misdirection or perforation. Consequently, the findings presented herein offer essential evidence-based guidelines for the handling and storage of 3D-printed endoguides within clinical workflows, thereby providing a novel contribution to the digital endodontics literature.

However, the study has certain limitations. Firstly, it is an ex vivo study that does not include teeth with root canal calcifications. Futhermore, the clinical relevance of the simulated laboratory model warrants further discussion. The model utilised in this study was deliberately designed to replicate a narrow and elongated canal axis, thereby simulating the anatomical characteristics of calcified canals. However, the absence of a guide derived from a real clinical case may be considered a limitation in terms of clinical generalizability [12, 22]. This approach was deliberately chosen to ensure a high level of standardisation, allowing the isolated evaluation of the effects of storage conditions and duration on dimensional stability. The utilisation of guides derived from actual patients would have introduced anatomical variability, potentially compromising the precision and comparability of the measurements. Consequently, subsequent studies should seek to build upon these findings by incorporating clinically derived models to validate the results under more realistic, patient-specific conditions. Future research would benefit from including different resin types with varying compositions and printers utilising different technologies to broaden the scope of findings. Additionally, only a single material type—Biomed Clear Resin—was used in this study. Although Biomed Clear Resin is an acrylic-based biomaterial, its responses to environmental conditions (such as light, darkness, humidity, and dryness) could not be compared with those of other types of acrylic resins. This limitation makes it difficult to discern whether the observed effects are attributable to the material itself or to the design of the endodontic guide. In future studies, preliminary tests using samples fabricated from the same type of acrylic should be conducted to better elucidate the influence of these variables, and the results should be compared accordingly.

Conclusion

This study demonstrated that the dimensional accuracy of endodontic guides produced using 3D printing technology is influenced by both storage duration and storage conditions. Specifically, it was found that storage in humid environments and prolonged storage durations had a negative impact on the dimensional stability of the guides. Based on these findings, it is recommended that endodontic guides be used as soon as possible after production and stored in dry, dark environments to maintain their accuracy.

Abbreviations

CBCT	Cone-Beam Computed Tomography
DD	Dry-Dark
DL	Dry-Light
SPSS	Statistical Package for the Social Sciences
STL	The Standard Tessellation Language
WD	Wet-Dark
WL	Wet-Light

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Author contributions
YEO: Conceptualization, Methodology, Writing– Original Draft Preparation, and Visualization. IO: Data Curation, Formal Analysis, Investigation, Resources, and Writing. ZOK: Statistical Analysis, Software, Data Analysis, Validation, and Writing– Review & Editing. EK: Supervision, and Writing– Review & Editing. All authors have read and approved the final version of the manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
This study does not require ethical approval as it did not involve the use of human subjects or human-derived tissues. All experimental procedures were conducted using synthetic materials, thereby exempting the research from the necessity of ethical review.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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