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Idil Ozden, Yunus Emre Ozden, Zeynep Ozkurt Kayahan & Hesna Sazak Ovecoglu

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Comparative Evaluation of Different Layer Thickness in 3D-Printed Endodontic Guides: An In vitro Study

Idil OZDEN[1], Yunus Emre OZDEN[2], Zeynep OZKURT KAYAHAN[2], Hesna SAZAK OVECOGLU[1]

[1] Marmara University Faculty of Dentistry Department of Endodontics, Istanbul, Turkiye

[2] Yeditepe University Faculty of Dentistry Department of Prosthodontics, Istanbul, Turkiye

Corresponding author:

Idil OZDEN

Basibuyuk Road Marmara University, Health Campus 9/3, 34854 Maltepe/Istanbul/TURKEY

idil.akman94@gmail.com

+905343400023

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Declarations

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Competing Interest: The authors declare that there are no financial or non-financial conflicts of interest.

Ethics declaration: 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.

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Abstract

Background: Guided endodontics has become essential for achieving minimally invasive and predictable access cavity preparation in advanced canal obliteration. However, the dimensional accuracy of endodontic guides depends on several 3D printing parameters, particularly layer thickness. This in vitro study evaluated the effect of two different layer thicknesses—50 µm and 100 µm—on the dimensional accuracy of stereolithographically printed endodontic guides.

Methods: Twenty-four endoguides were produced using a Form 3B+ printer (Formlabs, USA) with Biomed Clear Resin V2. Layer thickness was the only variable, while other printing parameters were standardized. After post-processing, specimens were scanned with a 3Shape E1 scanner, and STL files were superimposed using MeditDesign software. Dimensional deviations were calculated as root mean square (RMS, mm) values. Data were analyzed using an independent samples t-test ($p < 0.05$).

Results: Guides printed at 50 µm showed a mean RMS deviation of 0.066 ± 0.019 mm, while those printed at 100 µm exhibited 0.106 ± 0.035 mm ($p = 0.002$). Thinner layers resulted in significantly higher dimensional accuracy.

Conclusion: Within the limitations of this in vitro study, reducing layer thickness significantly improved the dimensional fidelity of 3D-printed endodontic guides. However, although this difference was statistically significant, its clinical relevance should be interpreted with caution, as the absolute deviations observed in both groups were in the range of approximately 0.1 mm.

Keywords: endoguide, 3D printing, layer thickness, dimensional accuracy.

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Introduction

The accurate preparation of the access cavity is a critical step that directly influences the success of endodontic treatment. However, in cases with advanced canal obliteration or complex root canal anatomy, conventional access cavity preparation can be technically challenging. In such cases, traditional approaches may increase the risk of unnecessary dentin loss and iatrogenic complications [1,2]. These complications, in turn, may lead to infection in inaccessible periapical tissues, thereby compromising the success of endodontic therapy [3]. Furthermore, even with the use of contemporary magnification and illumination techniques, access cavity preparation and identification of canal orifices remain difficult in severely calcified teeth. This difficulty often necessitates excessive removal of tooth structure, which may result in a poor long-term prognosis [4,5].

In recent years, advances in computer-aided design (CAD) and three-dimensional (3D) printing technologies have introduced the concept of guided endodontics into clinical practice. Guided endodontics has emerged as an alternative treatment modality for teeth with partially or completely obliterated pulp canals [6]. This approach enables the creation of the planned canal pathway in a minimally invasive manner and provides predictable outcomes regardless of operator experience. The 3D printing workflow involves acquiring digital data through an intraoral scanner and/or CBCT, processing and designing the data using computer software, and subsequently fabricating a template via additive manufacturing. This advanced technique not only improves time efficiency during the procedure but also ensures a favorable prognosis with a reduced risk of complications [6-9]. A wide range of techniques and materials are currently available on the market for the fabrication of dental guides. The selection of material and printing techniques is of critical importance with respect to biocompatibility, sterilization protocols, and printing accuracy.

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In 3D printing, digital designs are precisely fabricated in a layer-by-layer manner. Layer thickness refers to the height of material deposited in each pass of the 3D printer, and it directly influences the surface quality, mechanical properties, and dimensional accuracy of the final product. During the layer-by-layer fabrication process, each new layer adheres to and cures on the surface of the previous one. When the layer thickness is reduced, improved light penetration and more uniform photopolymerization can be achieved, resulting in a higher degree of conversion and stronger interlayer bonding between successive layers [10]. Conversely, with thicker layers, variations in the degree of polymerization between the lower and upper portions of the material may occur during curing. Such discrepancies can lead to incomplete polymerization in deeper regions or excessive shrinkage, resulting in stress accumulation and dimensional deviations [11]. Layer thickness is therefore critical not only for dimensional accuracy but also for production efficiency. While thicker layers reduce manufacturing time, thinner layers enhance dimensional precision at the expense of longer printing times [12,13]. In the interface software of 3D printers, layer thickness is typically provided as an adjustable parameter.

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Previous studies have examined the effects of layer thickness in the fabrication of surgical guides, restorative materials, and dies; however, research specifically investigating how different layer thicknesses affect the ability of endodontic guides to accurately reach the root apex remains limited [14-16]. The situation in endodontic guides is more critical than in surgical guides, as the working field of root canal systems is far more confined and requires millimetric precision compared with implant osteotomies. Even a slight misalignment in the location or angulation of the access cavity may lead to unnecessary dentin removal, perforation, or failure to reach the target canal [17]. Consequently, minor geometric discrepancies arising from printing resolution may translate into clinically significant complications. Therefore, clarifying the influence of production parameters—particularly layer thickness—on the dimensional accuracy of endodontic guides is of paramount importance for ensuring safe and predictable clinical applications. Accordingly, the present study aimed to evaluate the effect of two different layer thicknesses (50 µm and 100 µm) on the manufacturing-related dimensional accuracy of stereolithographically printed endodontic guides, with a specific focus on geometric deviations at the apical region of a simulated canal pathway. The null hypothesis of this study was that there would be no significant difference between endodontic guides fabricated with different layer thicknesses (50 µm and 100 µm) in terms of manufacturing-related dimensional accuracy at the apical region, as assessed by RMS-based surface deviation analysis.

Material and Methods

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.

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In this in vitro study, the effect of layer thickness on the dimensional accuracy of endodontic guides was investigated (Figure 1). The sample size of n = 12 per group was determined based on sample sizes commonly used in comparable in vitro studies evaluating dimensional accuracy of 3D-printed dental guides [18,19]. In addition, an a priori power analysis was performed using a two-tailed independent samples t-test ($\alpha = 0.05$, $1-\beta = 0.80$), assuming a large effect size, which is consistent with previously reported differences in manufacturing-related dimensional outcomes. Under these assumptions, a minimum of 12 specimens per group was considered sufficient to achieve 80% statistical power.

A total of 24 guides were fabricated with two different layer thicknesses, 50 µm (Group-50) and 100 µm (Group-100). All guides were manufactured using the same printer, the same resin, and a single batch number to minimize variability. The guides were designed in BlueSky Plan software (Blue Sky Bio, IL, USA), exported in STL format, and optimized for placement and support structures prior to printing using PreForm software (Formlabs Inc., Somerville, USA). To enable standardized and reproducible assessment of manufacturing-related dimensional deviations, a simplified cylindrical reference structure was integrated into the guide design. This structure did not aim to replicate the anatomical complexity of a root canal or represent a clinical target for canal advancement but rather served as a predefined geometric reference for deviation analysis, particularly at the apical region. The reference cylinder had a diameter of 1.0 mm and a length of 12 mm and was designed as a straight geometry with parallel walls to provide a standardized and reproducible region of interest for RMS-based deviation analysis. (Figure 2).

All specimens were fabricated using a Form 3B+ stereolithography (SLA) printer (Formlabs Inc., Somerville, MA, USA) with Biomed Clear Resin V2, a Class II biocompatible rigid resin (Formlabs Inc., Somerville, MA, USA). Printing was performed in a horizontal orientation, with layer thickness (50 µm or 100 µm) as the sole variable between the groups; all other printing parameters were kept constant. Post-processing procedures were carried out strictly in accordance with the manufacturer's specific recommendations for Biomed Clear Resin V2. Accordingly, the printed guides were washed in 99% isopropyl alcohol for 8 minutes using a Form Wash unit, air-dried for 10 minutes, and subsequently post-cured for 30 minutes at 60 °C using 405-nm light in a Form Cure unit. After post-curing, support structures were removed, and the contact points were positioned so as not to interfere with subsequent measurements. All specimens were stored in a dry and dark environment at 23 ± 1 °C for 24 hours prior to scanning.

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The fabricated guides were digitized using a desktop laboratory scanner (3Shape E1; 3Shape A/S, Copenhagen, Denmark), and the resulting mesh data were saved in STL format. The original design STL files were defined as the reference dataset, whereas the scanned STL files were defined as the test dataset. Superimposition of the reference and test datasets was performed using Medit Design software (Medit Inc., Seoul, South Korea). Following an initial global alignment, a fine best-fit alignment was performed using the manually selected internal surfaces of the endodontic guides to improve correspondence between the datasets. Dimensional deviations between the aligned datasets were calculated as root mean square (RMS, mm) surface deviations (Figure 3). The apical region of the simulated root canal structure was defined as the region of interest for deviation analysis (Figure 4).

Statistical Analysis

The data were analyzed using IBM SPSS version 31 (IBM Corp., Armonk, NY, USA). The normality of data distribution was assessed using both statistical and graphical methods. Descriptive statistics were presented as mean, standard deviation, and interquartile range (IQR). Comparisons of RMS value distributions according to layer thickness were performed using the Independent Samples t-test. A Type I error rate of 5% ($\alpha = 0.05$) was adopted for all analyses.

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Results

The distribution of RMS values according to the layer thickness of the fabricated endoguides is presented in Table 1. For the Goup-50, the mean RMS value was 0.066 ± 0.019 mm with an IQR of 0.036, whereas for the Group-100, the mean RMS value was 0.106 ± 0.035 mm with an IQR of 0.037. The difference between the two thickness groups was statistically significant (Independent Samples t-test, $p = 0.002$).

Discussion

The acceleration of digitalization in dentistry has markedly increased the significance of 3D printing, also referred to as additive manufacturing, technologies. In particular, there has been a remarkable rise in research focusing on the fabrication of resin-based restorative materials using 3D printing methods. These studies encompass a wide spectrum, ranging from the types

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of printers employed to the varieties and compositions of resins, as well as post-processing steps such as washing, drying, curing, and other finishing procedures [20-22]. Research in this field has predominantly focused on properties such as color stability, mechanical strength, surface roughness, surface hardness, cytotoxic potential, and resistance to bacterial accumulation 12,13]. However, factors such as post-production storage conditions and the polymerization process have also emerged as important areas of investigation due to their influence on the dimensional stability of the materials [18].

Due to their composition, resin-based materials frequently exhibit dimensional changes associated with polymerization shrinkage. In restorative applications, this phenomenon may lead to marginal or internal misfit. Similarly, dimensional deviations occurring during the fabrication of surgical or endodontic guides can directly influence their accuracy and clinical reliability. Most previous studies on 3D-printed endoguides have consisted of case reports and preclinical investigations, which have demonstrated promising outcomes and potential advantages, such as reduced operative time and a lower risk of procedural errors [19,23,24]. However, research evaluating the parameters that affect the precision of these materials remains limited. In light of the findings obtained in the present study, which assessed the influence of layer thickness variation on the dimensional accuracy of endodontic guides, the null hypothesis was rejected.

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In the literature, studies evaluating the effect of layer thickness on dimensional stability in various dental applications have reported inconsistent results. For example, in a study assessing the dimensional stability of 3D-printed dies, layer thicknesses of 25, 50, and 100 µm were compared, and significantly greater dimensional deviations were observed at 100 µm compared with 25 and 50 µm [25]. Similarly, in another investigation examining dimensional deviations of the internal surfaces and angular deviations of the guide sleeves in implant surgical guides, 50 µm and 100 µm layer thicknesses were evaluated, with fewer dimensional deviations reported at 50 µm [13]. In addition, a study evaluating the marginal and internal fit of 3D-printed PMMA crowns compared 25, 50, and 100 µm layer thicknesses, and recommended 50 µm as the most favorable thickness with respect to both fit parameters [26]. These findings are consistent with the results of the present study.

On the other hand, the findings of the present study contradict the only study in literature that has directly evaluated the relationship between layer thickness and the dimensional accuracy of endoguides. In their study, Kamburoğlu et al. [19] assessed guide accuracy by fabricating three different resin types at two different layer thicknesses. The authors reported no statistically significant differences in accuracy between guides produced with 50 µm and 100 µm layer thicknesses for any of the resin types tested. This discrepancy may be attributed to methodological differences and measurement strategies employed in the two studies. Specifically, Kamburoğlu et al. [19] evaluated guide accuracy using linear and angular deviations derived from postoperative CBCT images. However, CBCT, due to its voxel size (0.08 mm) and inherent imaging limitations, may be insufficient to detect micron-level dimensional differences potentially induced by variations in layer thickness. In contrast, the present study employed high-resolution STL datasets obtained with a laboratory-grade desktop scanner, and surface-based RMS analyses were performed in MeditDesign software. This method calculates surface deviations in three dimensions and is therefore capable of directly and more sensitively capturing minor geometric irregularities resulting from differences in layer thickness during fabrication. Moreover, while only five specimens per group were analyzed in the previous study, the present research included twelve specimens per group, thereby enhancing the sensitivity of statistical testing and enabling the detection of even small but systematic deviations. Additionally, the earlier study simultaneously tested both material type (Dental SG, Gray, High Temp resins) and layer thickness, introducing additional variance due to differences in polymerization shrinkage, thermal expansion, and post-processing protocols

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across materials. In the present investigation, however, a single resin type (Biomed Clear V2) was used, with layer thickness as the only variable, while all other parameters were kept constant. This approach allowed for a clearer assessment of the specific influence of layer thickness on guide accuracy.

In 3D printing systems, layer thickness directly influences production resolution [20]. But in the literature, no standard layer thickness has been defined for the fabrication of endoguides. It s hould also be acknowledged that the "optimal" layer thickness may not be universal and could vary depending on resin-specific factors such as optical opacity, light transmission characteristics, and the concentration and type of photo-initiator, all of which influence polymerization behavior during stereolithographic printing. As resolution and detail increase, production time correspondingly becomes longer; for instance, while fabrication at 100 µm can be completed within 1 hour, production at 25 µm may extend up to 6 hours [12,13,27]. For this reason, the present study evaluated 100 µm and 50 µm thicknesses, as they are more adaptable to clinical application. The difference between these two-layer thicknesses was found to be statistically significant. Nevertheless, the clinical relevance of the observed difference should be interpreted with caution. Although the approximately 40 µm difference in RMS values identified in the present study was statistically significant, it remains relatively small in absolute terms when compared with the diameter of a typical endodontic bur, which generally ranges between 0.8 and 1.0 mm. Therefore, such a difference alone would not be expected to directly result in clinically perceptible misguidance or procedural failure. However, in guided endodontics, accuracy is not determined by a single parameter but rather by the cumulative effect of multiple factors, including guide–tooth adaptation, guide stability, bur system tolerances, and operator-related variables.

In guided endodontics, even a small linear deviation at the guide level can translate into a disproportionately larger positional error at the apical region when a long drill or bur is used.

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This phenomenon is attributable to the lever-arm effect, whereby minor deviations at the coronal or guiding interface may be amplified along the length of the drill, resulting in increased angular discrepancy at the tip. Consequently, while angular deviation was not directly assessed in the present study, the observed dimensional differences may have greater clinical relevance in scenarios involving deep access preparation or severely calcified canals, where precision at the apical level is critical.

In this study, the endodontic guides were manufactured using horizontal printing orientation. The primary rationale for selecting this orientation was its advantage in reducing printing time and minimizing the need for support structures, while providing more homogeneous layer formation and higher surface accuracy, particularly at the intaglio surfaces. In stereolithographic printing, fabrication time is largely dependent on the number of layers; therefore, horizontal orientation requires fewer layers and offers improved manufacturing efficiency [28]. In addition, the guides were designed as sleeveless, and no metal or polymer guiding sleeve was incorporated. This design choice was intended to eliminate potential tolerance errors associated with sleeve–drill interaction and geometric deviations arising from sleeve positioning. Consequently, any potential influence of printing orientation on sleeve fit does not constitute a clinical or methodological limitation within the scope of the present study.

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This study has several limitations that should be acknowledged. First, no tooth model was used, and guide–tooth adaptation was not evaluated. Therefore, clinically relevant factors such as guide stability, fit, and spatial relationship between the guide and tooth anatomy were not assessed. Although the present study did not include a direct clinical or tooth-based outcome measure, it was intentionally designed to isolate the effect of a single manufacturing parameter—layer thickness—on the geometric fidelity of endodontic guides. In guided endodontics, overall clinical accuracy is the result of multiple interdependent factors, including guide design,

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printing accuracy, guide–tooth adaptation, bur–guide tolerances, and operator-related variables. Evaluating all these parameters simultaneously may obscure the specific contribution of individual factors. Therefore, assessing dimensional deviations at the manufacturing level represents a necessary preliminary step toward understanding how cumulative inaccuracies may arise in clinical applications. Second, no guided drilling or mechanical canal preparation was performed; consequently, functional outcomes such as canal negotiation accuracy, deviation from the planned trajectory, or the amount of dentin removed could not be evaluated. Third, the assessment was limited to STL-based RMS surface deviation analysis, which reflects manufacturing-related geometric accuracy only. Linear or angular deviations, which may be more directly related to clinical performance, were not measured. Accordingly, the findings should be interpreted as reflecting dimensional fidelity under controlled manufacturing conditions rather than functional or clinical guided endodontic accuracy. Furthermore, this investigation was conducted exclusively under in vitro conditions, and thus the accuracy and success of the guides in a clinical setting were not assessed.

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Conclusion

Within the limitations of this in vitro study, layer thickness was shown to have a statistically significant effect on the manufacturing-related dimensional accuracy of 3D-printed endodontic guides. Guides fabricated with a 50 µm layer thickness exhibited lower RMS surface deviations compared with those produced at 100 µm. However, these findings should be interpreted strictly within a technical context, as no clinically defined tolerance thresholds, guided drilling procedures, or tooth-based references were included. Therefore, the results reflect differences in manufacturing fidelity rather than clinical acceptability or functional guided endodontic performance.

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Tables

Table 1: Distribution of RMS values of endoguides according to layer thickness

Layer Thickness	RMS		
	Mean	**Standard Deviation**	**IQR**
Group-50 (n=12)	0,066	0,019	0,036
Group-100 (n=12)	0,106	0,035	0,037

IQR: Interquartile Range (IQR)

Independent Samples t-test, $p = 0.002$

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Figures

Figure 1: Schematic workflow of the study illustrating the digital design, fabrication, post-processing, scanning, and STL–STL superimposition steps used for RMS-based dimensional deviation analysis of 3D-printed endodontic guides.

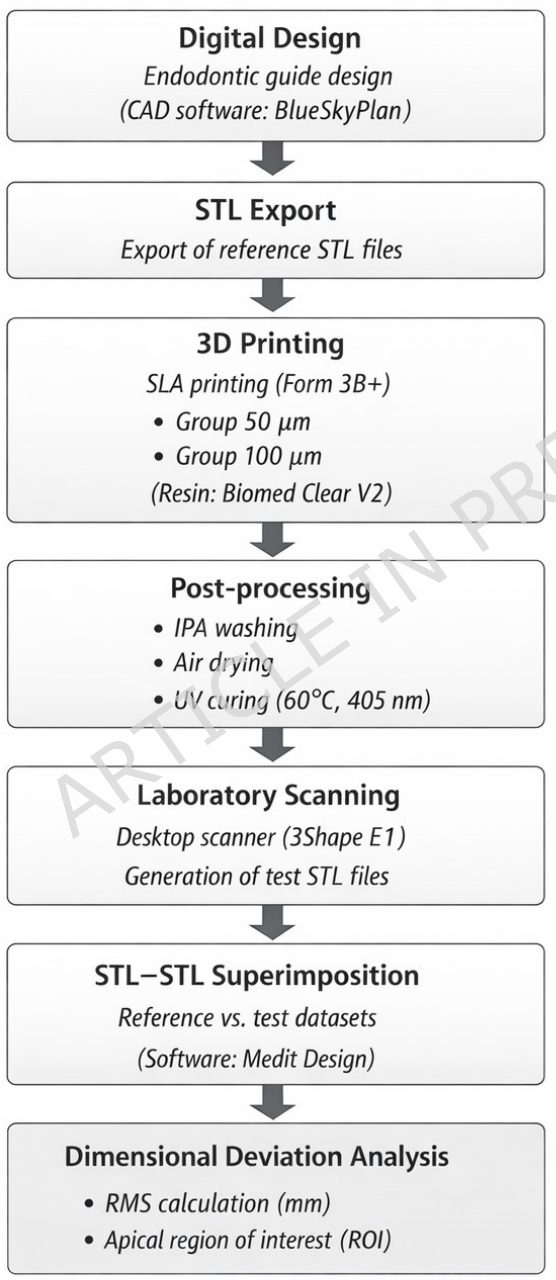

Figure 2: Color-coded definition of the apical region of interest and the superimposition area used for STL–STL comparison.

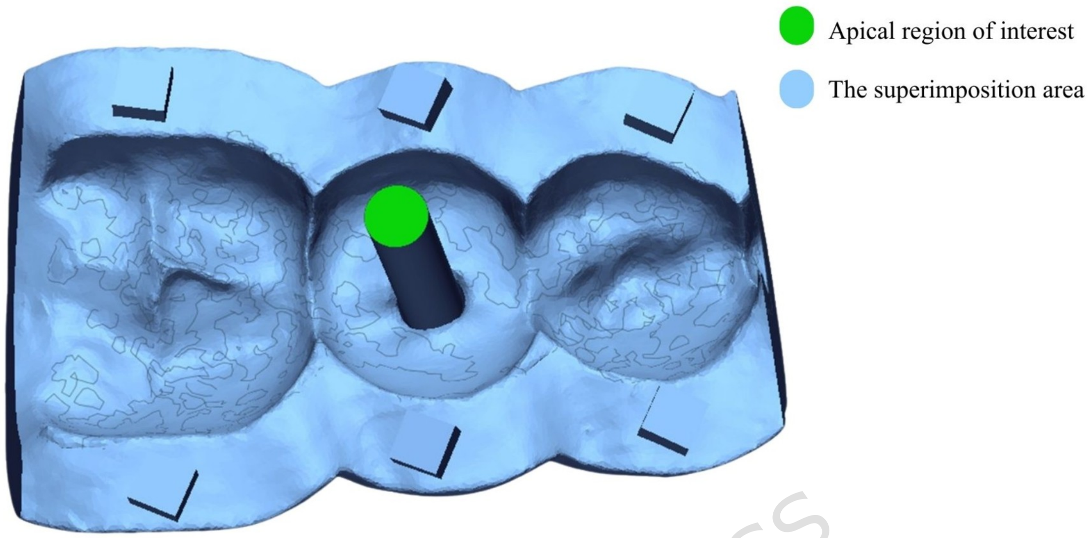

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Figure 3: Superimposition of the reference (design) and test (printed) STL datasets in MeditDesign software for dimensional deviation analysis.

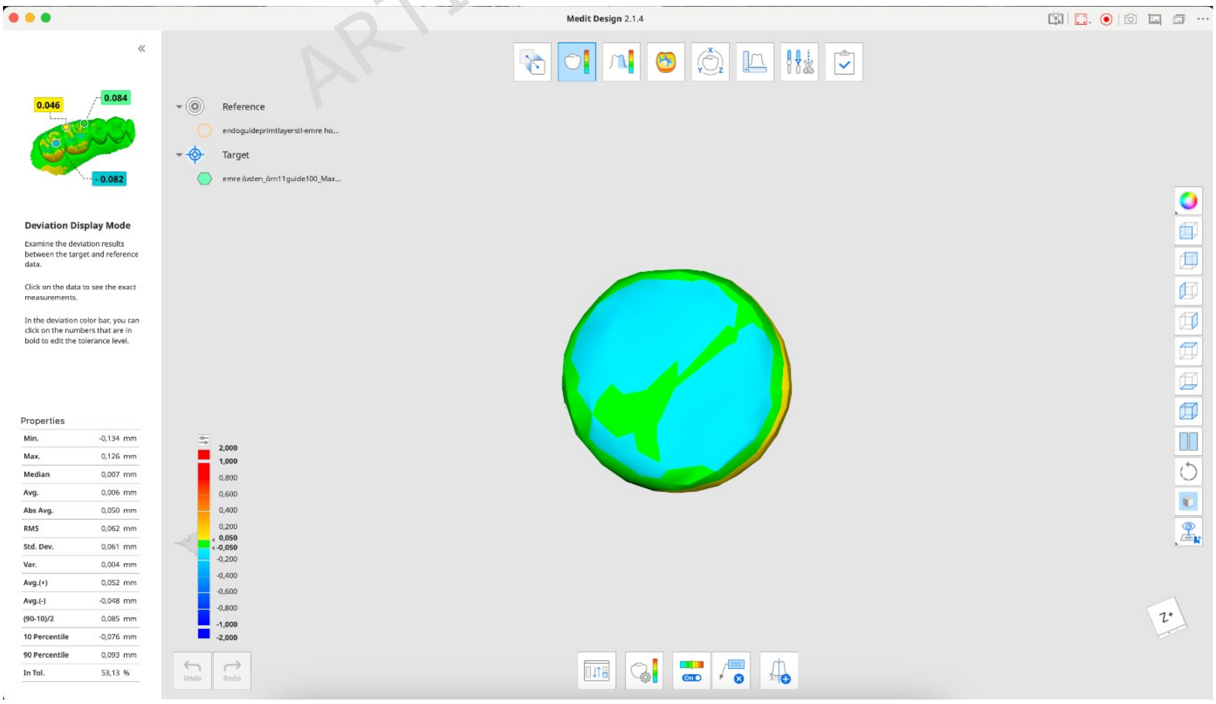

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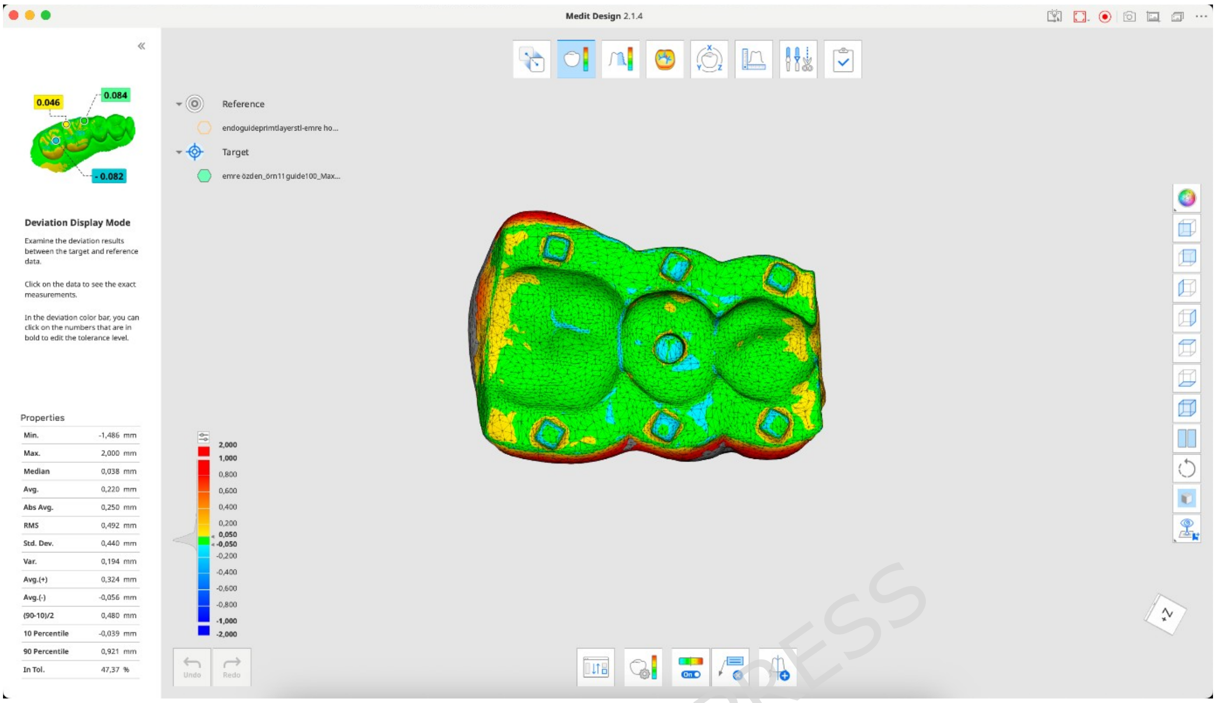
Figure 4: Two-dimensional color map representing the root mean square (RMS) deviation values across the measured surface area, illustrating local accuracy variations.



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