The Effect of Nozzle Diameter on the Dimensional Accuracy of FDM-Printed Dental Models

https://doi.org/10.70921/medev.v32i1.2030

Marius Ciprian Manole[1], Alexandru Victor Burde[2*], Alexandru Grecu[1], Mihaela Hedeşiu[1], Cosmin Sinescu[3,4]

[1]*Faculty of Dental Medicine, "Iuliu Haţieganu" University of Medicine and Pharmacy, 32 Clinicilor Street, 400394 Cluj-Napoca, Romania*
[2]*Faculty of Nursing and Health Sciences, "Iuliu Haţieganu" University of Medicine and Pharmacy, 8 Victor Babes Street, 400012 Cluj-Napoca, Romania;*
[3]*Faculty of Dental Medicine, "Victor Babes" University of Medicine and Pharmacy of Timisoara, 2 Eftimie Murgu Square, 300041 Timisoara, Romania;*
4Research Center in Dental Medicine Using Conventional and Alternative Technologies, Department of Prostheses Technology and Dental Materials, Faculty of Dental Medicine, "Victor Babes" University of Medicine and Pharmacy of Timisoara, 9 Revolutiei 1989 Ave., 300070 Timisoara, Romania

Correspondence to:
Name: Alexandru Victor Burde
E-mail address: burde.alexandru@umfcluj.ro

Received: 06 March 2026; Accepted: 11 March 2026; Published: 31 March 2026

Abstract

Additive manufacturing has become an integral component of the digital workflow in dentistry. Among available technologies, fused deposition modeling (FDM) offers a cost-effective alternative for producing dental models, although concerns remain regarding dimensional accuracy. The aim of this study was to evaluate the influence of nozzle diameter and dental arch morphology on the dimensional accuracy of FDM-printed dental models. Reference STL datasets representing ideal maxillary and mandibular arches were printed using a Bambu Lab X1 Carbon printer with two nozzle diameters (0.2 mm and 0.4 mm) in a 2 × 2 factorial design (n = 40). Dimensional accuracy was assessed using Root Mean Square (RMS) deviation obtained through 3D surface comparison. Models printed with the 0.2 mm nozzle demonstrated significantly lower RMS deviations compared with those printed using the 0.4 mm nozzle. Additionally, mandibular models exhibited higher dimensional stability than maxillary models. These findings indicate that smaller nozzle diameters can improve the accuracy of FDM-printed dental models.

Keywords: Fused Deposition Modeling, Additive Manufacturing, Dental Models, Dimensional Accuracy, Nozzle Diameter, Digital Dentistry, 3D Printing

INTRODUCTION

The transition toward the concept of Dentistry 4.0 has positioned additive manufacturing (AM) as a central component of the contemporary digital workflow in dentistry and dental technology [1]. Through the conversion of conventional impressions into high-resolution digital datasets, AM enables the rapid fabrication of complex dental geometries that would be difficult or time-consuming to obtain using traditional subtractive manufacturing methods [2]. Within the clinical dental practice, vat polymerization technologies such as stereolithography (SLA) and digital light processing (DLP) have been widely adopted due to their high surface quality and micron-level resolution [3,4]. However, the relatively high cost of proprietary photopolymer resins and the requirement for post-processing using chemical solvents have stimulated interest in more accessible and cost-effective manufacturing alternatives [5].

In this context, fused deposition modelling (FDM), also referred to as fused filament fabrication (FFF), has gained increasing attention within the dental field [6]. This technology offers several advantages, including lower equipment costs, a broad range of thermoplastic materials such as PLA, PETG, or PEEK, and a production workflow that does not involve liquid resins or chemical post-processing steps [7]. Nevertheless, the use of FDM for dental restorations remains limited due to concerns related to dimensional accuracy and structural anisotropy of the printed components [8]. Common limitations include the staircase effect on inclined surfaces, volumetric shrinkage during cooling, and reduced interlayer adhesion, all of which may negatively influence the precision required in dental applications [9]. Despite these limitations, FDM technology has demonstrated promising potential for the fabrication of dental study models, orthodontic aligner templates, and diagnostic casts [10]. In such applications, dimensional accuracy of the printed arch is essential, as even minor deviations may compromise the fit of vacuum-formed appliances or affect the interpretation of occlusal relationships. Consequently, recent studies have focused on the optimization of printing parameters in order to improve the accuracy of FDM-produced dental models, with nozzle diameter emerging as a critical factor [11].

The nozzle diameter represents the primary parameter governing the extrusion width of the deposited filament and therefore determines the minimum feature size achievable during printing [12]. While the standard 0.4 mm nozzle is generally preferred due to its higher printing speed and reliable extrusion, it may lack the resolution required to accurately reproduce fine dental anatomical details such as occlusal grooves or preparation margins [13]. The use of smaller nozzle diameters, such as 0.2 mm, can theoretically improve the fidelity of printed structures by reducing extrusion width and allowing a closer approximation of the digital STL geometry [14]. In addition, the interaction between nozzle diameter and the specific morphology of dental arches remains insufficiently investigated, particularly considering that the different geometries of maxillary and mandibular arches may influence thermal behaviour and cooling dynamics during the printing process. In light of these considerations, further investigation is required to clarify the influence of nozzle diameter and anatomical morphology on the dimensional accuracy of FDM-printed dental models.

Aim and objectives

The aim of this study was to evaluate the effect of nozzle diameter and arch morphology on the dimensional accuracy of dental models fabricated using fused deposition modeling (FDM) and to determine whether smaller nozzle diameters improve the trueness of printed models when compared with the standard 0.4 mm configuration.

MATERIAL AND METHODS

An in vitro experimental protocol was designed to investigate the influence of nozzle diameter and arch morphology on the dimensional accuracy of dental models manufactured using fused deposition modeling.

In order to establish the control dataset, one ideal maxillary arch and one ideal mandibular arch in STL format were selected as reference models. These represented anatomically complete and well-aligned dentitions without restorations, missing teeth, or pathological features. The reference models were characterized by regular arch morphology, complete dentition from second molar to second molar, and anatomically defined occlusal and interproximal structures typical of a standard dental arch. Such standardized geometries were selected in order to minimize anatomical variability and to allow a controlled evaluation of the influence of printing parameters on dimensional accuracy.This approach ensured that the observed dimensional deviations were primarily attributable to the printing parameters rather than variations in patient-specific anatomical complexity.

Printable models were generated by using dental CAD software Exocad version 3.2 (Exocad GmbH, Darmstadt, Germany). These reference models were designed in a hollow-base configuration to reduce material consumption and printing time while maintaining structural stability. A uniform base was defined and the optimal insertion axis was established to facilitate digital processing and manufacturing. Wall thickness was set to 2.5 mm to ensure adequate mechanical stability. Each model was visually inspected to verify margin integrity and correct spatial orientation before export in STL format.

Preparation for fused deposition modeling (FDM) printing was carried out using Bambu Studio software (version 2.4.0.70). The STL models were imported into the slicing software, where the printing parameters were configured prior to manufacturing. All specimens were produced using a Bambu Lab X1 Carbon 3D printer (Bambu Lab, Shenzhen, China) and Bambu PLA Basic White filament. PLA was selected as the printing material due to its widespread use in fused deposition modeling and its good dimensional stability during printing. Compared with other thermoplastics such as ABS or PETG, PLA exhibits lower thermal shrinkage, reducing the risk of warping and facilitating the fabrication of accurate dental models. However, PLA has lower thermal resistance and mechanical strength than medical-grade polymers, which may limit its use in applications requiring higher mechanical performance. The layer height was set to 0.08 mm, corresponding to the highest quality setting for both nozzle configurations evaluated in this study (0.2 mm and 0.4 mm). The number of perimeters was set to three to ensure adequate wall stability, while the seam position was configured as aligned to maintain consistent layer junction positioning during printing. The internal structure of the models was defined using a 15% gyroid infill pattern, selected for its favorable balance between mechanical stability and material efficiency. All relevant printing parameters used for the fabrication of the dental models are summarized in Table 1.

Table 1. Summary of printing parameters used in the study

Parameter	Value
Nozzle diameter	0.2 mm / 0.4 mm
Material	PLA
Layer height	0.08 mm
Initial layer height	0.10 mm
Line width	0.22 mm
Extrusion temperature	210 °C
Build plate temperature	60 °C
Cooling fan speed	70%
Outer/ **Inner** wall speed	60/150 mm/s

Infill density	15%
Infill pattern	Gyroid
Number of wall loops	4
Top shell layers	7
Bottom shell layers	5
Support structures	None
Bed adhesion	5 mm brim

After finalizing the printing parameters, the models were sliced and exported as G-code files, which were subsequently transferred to the printer for fabrication (Figure 1).

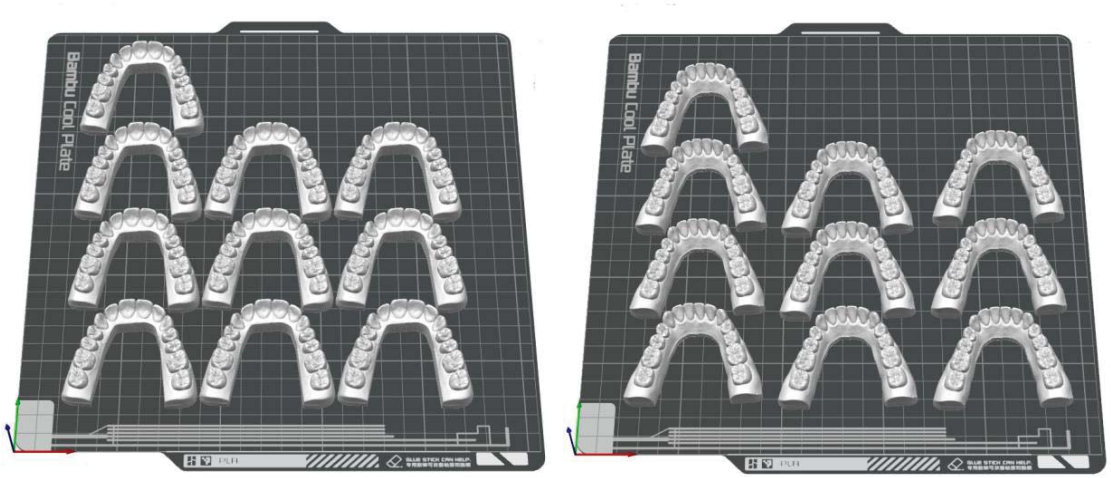

Figure 1. Build platform layout of the maxillary and mandibular models prepared for fused deposition modelling (FDM)

Before each printing session, the filament spool was mounted on the dedicated holder and the filament tip was cut at an oblique angle to facilitate insertion into the extruder. The build platform was cleaned before every printing cycle using 99.8% isopropyl alcohol (Kontakt IPA Plus, TermoPasty, Poland) applied with a non-abrasive wipe to remove dust, grease, or adhesive residues that could compromise first-layer adhesion. The printer uses a magnetic build platform with a removable flexible spring-steel plate, allowing easy removal of printed models. A smooth build plate surface was used throughout the experiment. Before each printing cycle, the printer performed an automatic calibration procedure including first-layer calibration.

The experimental design followed a 2 × 2 factorial structure, with nozzle diameter (0.2 mm and 0.4 mm) and dental arch type (maxillary and mandibular) as independent variables. Four experimental groups were generated, each group consisting of ten models (N = 40): maxilla printed with a 0.4 mm nozzle (Figure 2 A), mandible printed with a 0.4 mm nozzle (Figure 2 B), maxilla printed with a 0.2 mm nozzle, and mandible printed with a 0.2 mm nozzle. All specimens were fabricated using the same printer. Initially, the models were printed using a 0.4 mm nozzle, and after completion of the first set of specimens, the nozzle was replaced with a 0.2 mm nozzle. The nozzle replacement procedure was performed in accordance with the manufacturer's specifications.

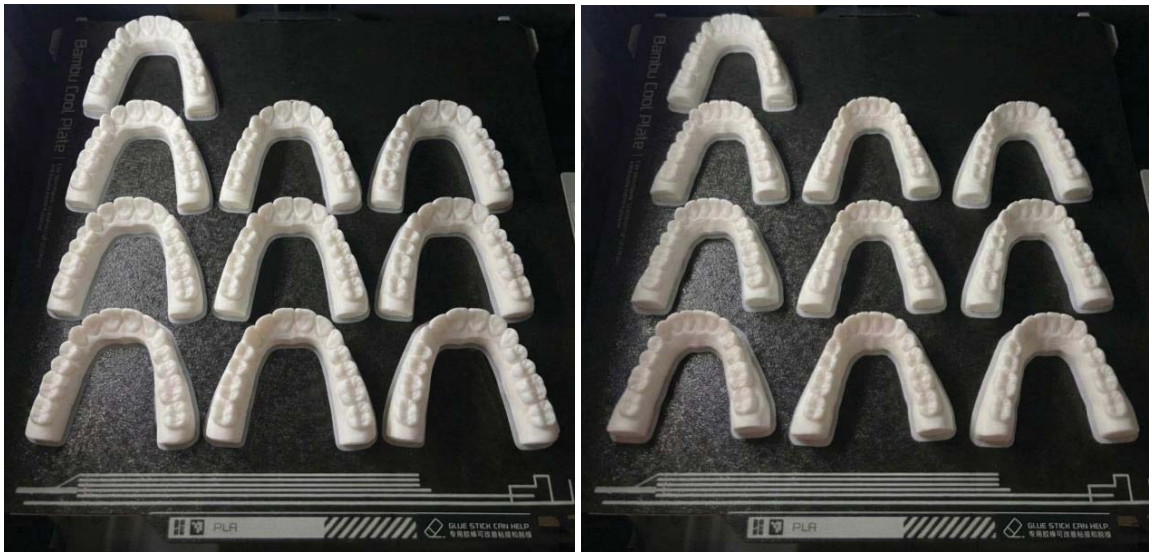

Figure 2. Printed dental models: (A-left) maxillary and (B-right) mandibular models printed with the 0.4 mm nozzle

After fabrication, all printed models were digitized using the InEos X5 laboratory scanner (Dentsply Sirona, Bensheim, Germany), a high-precision extraoral scanning system with a reported accuracy of up to 2 µm. Each model was inspected before scanning to ensure that it was complete, stable, and free of contaminants. Scanning was performed within the inLab 15 software (Dentsply Sirona, Bensheim, Germany), where a digital case was created for each specimen and assigned a unique identification number. The scanner's robotic arm captured the geometry from multiple angles, ensuring complete coverage of dental and gingival surfaces. The acquired images were automatically aligned and merged to generate the final three-dimensional digital models. Dimensional accuracy was evaluated using Geomagic Control 2014 (3D Systems, Rock Hill, USA). Reference STL models and scanned STL files were imported into the software. Initial alignment was performed using a best-fit algorithm based on 300 corresponding points. The models were then trimmed and the alignment repeated using 3000 points, followed by a final alignment using 15,000 points to ensure accurate superimposition. The models were further trimmed near the alveolar ridge while preserving the cervical margins of the teeth.

The stepwise alignment strategy was applied to progressively refine the superimposition between the reference and test models, starting with a coarse registration step and followed by higher-resolution alignments to improve the stability and convergence of the best-fit algorithm prior to deviation analysis. Trimming of the models near the alveolar ridge was performed to standardize the comparison region among all specimens and to minimize potential artifacts generated by variations in the model base geometry. Consequently, the deviation analysis focused on the dentition surfaces, which represent the clinically relevant regions for orthodontic and diagnostic applications.

Dimensional comparison was performed using the "3D Compare" function, which calculates point-to-surface deviations between the reference and test models. The deviation thresholds were defined as +1000 µm (maximum deviation), +500 µm (critical positive deviation), +50 µm (normal positive deviation), −500 µm (critical negative deviation), and −50 µm (normal negative deviation). The analysis generated color-coded deviation maps where warm colors indicate positive deviations and cool colors indicate negative deviations. Quantitative accuracy was expressed using the Root Mean Square (RMS) deviation,

representing the square root of the mean of the squared distances between corresponding points.

Statistical analysis was performed using Python (version 3.10) with the NumPy and SciPy libraries. Data normality was assessed using the Shapiro–Wilk test, while homogeneity of variances was evaluated using Levene's test. The effects of nozzle diameter and arch type on dimensional accuracy were analyzed using two-way ANOVA with RMS deviation as the dependent variable. Statistical significance was set at $p < 0.05$.

RESULTS

Quantitative analysis was performed on 40 FDM-printed dental models, comprising 20 maxillary and 20 mandibular arches. Fabrication was executed using a Bambu Lab X1 Carbon system to compare two distinct nozzle diameters (0.2 mm and 0.4 mm). Accuracy was quantified through a 3D surface comparison, where the Root Mean Square (RMS) deviation (µm) served as the primary means for assessing the trueness of the printed models relative to the corresponding reference STL dataset.

Models printed with the 0.2 mm nozzle demonstrated consistently lower RMS deviation values compared with those fabricated with the 0.4 mm nozzle, indicating improved dimensional accuracy. Descriptive statistics showed that maxillary models printed with the 0.4 mm nozzle presented the highest RMS values (mean = 128.6 ± 8.7 µm), followed by mandibular models printed with the 0.4 mm nozzle (109.3 ± 7.6 µm). In contrast, lower RMS deviations were observed for models printed with the 0.2 mm nozzle, with maxillary models presenting a mean RMS of 93.0 ± 4.1 µm and mandibular models showing the lowest values (85.7 ± 6.1 µm). The distribution of RMS values across the four experimental groups is illustrated in Figure 3.

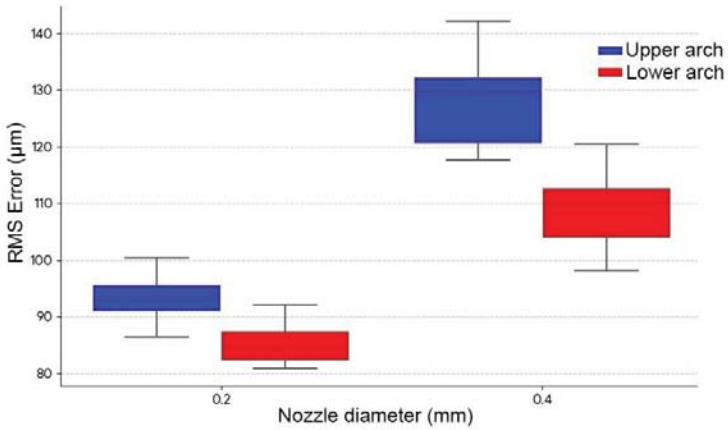

Figure 3. Comparison of Dimensional Accuracy (RMS Error) between 0.2 mm and 0.4 mm Nozzle Diameters for Maxillary and Mandibular Dental Models

The boxplot demonstrates a clear reduction in both median RMS values and dispersion for models printed with the 0.2 mm nozzle, suggesting improved geometric fidelity. Maxillary models printed with the 0.4 mm nozzle exhibited the largest variability, while mandibular models printed with the 0.2 mm nozzle showed the most consistent measurements.

Prior to inferential analysis, the assumptions required for parametric testing were evaluated. The Shapiro–Wilk test was applied to assess the normality of the RMS distributions within each group. Most datasets followed a normal distribution (Maxilla–0.4

mm: $W = 0.908$, $p = 0.265$; Mandible–0.4 mm: $W = 0.951$, $p = 0.677$; Maxilla–0.2 mm: $W = 0.965$, $p = 0.841$), while a slight deviation from normality was observed for Mandible–0.2 mm ($W = 0.801$, $p = 0.015$). Given the balanced experimental design (n = 10 per group) and the robustness of ANOVA to moderate deviations from normality, parametric analysis was considered appropriate.

Homogeneity of variances was evaluated using Levene's test, which confirmed that the assumption of equal variances across groups was satisfied ($F = 1.52$, $p = 0.226$).

In order to evaluate the influence of printing parameters and anatomical morphology on dimensional accuracy, a two-way analysis of variance (ANOVA) was performed with nozzle diameter (0.2 mm vs 0.4 mm) and dental arch (maxillary vs mandibular) as independent variables and RMS deviation as the dependent variable. The analysis revealed a statistically significant main effect of nozzle diameter (F (1,36) = 187.53, $p < 0.001$), indicating that models printed with the 0.2 mm nozzle exhibited significantly lower RMS deviations than those printed with the 0.4 mm nozzle. A significant main effect of arch type was also identified (F (1,36) = 37.88, $p < 0.001$), with mandibular models demonstrating lower RMS deviations compared with maxillary models. In addition, a statistically significant interaction between nozzle diameter and arch type was observed (F (1,36) = 7.69, $p = 0.0087$), suggesting that the magnitude of the improvement in dimensional accuracy associated with the smaller nozzle differed between the two dental arches. This interaction is illustrated in Figure 4, where the reduction in RMS deviation associated with the 0.2 mm nozzle appears more pronounced for maxillary.

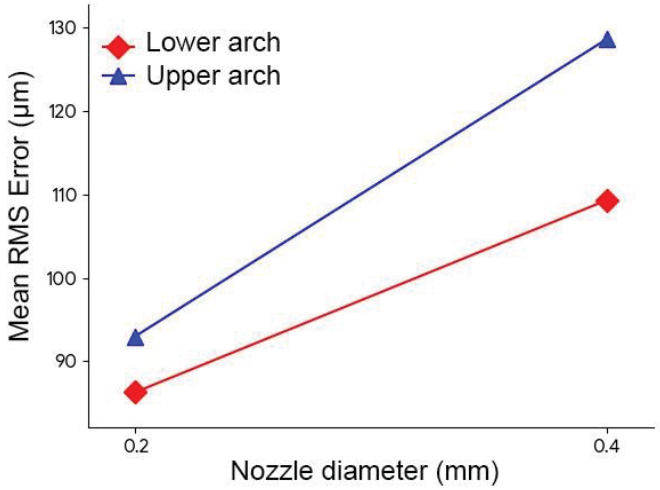

Figure 4. Interaction plot illustrating the combined effect of nozzle diameter and dental arch on RMS deviation values

To further verify the robustness of the findings, a non-parametric Kruskal–Wallis test was performed as a sensitivity analysis due to the slight deviation from normality observed in one group. The analysis confirmed a statistically significant difference in RMS deviation among the experimental groups ($p < 0.001$), supporting the results obtained from the parametric two-way ANOVA.

The color-coded deviation maps (Figure 5) illustrate the spatial distribution of dimensional differences between the printed models and the reference STL datasets. Models printed with the 0.2 mm nozzle show a more uniform deviation pattern, with larger areas within the green tolerance range (±50 µm), indicating higher trueness. In contrast, models produced with the 0.4 mm nozzle present more pronounced localized deviations, particularly on occlusal surfaces. These visual findings are consistent with the lower RMS values obtained

for the 0.2 mm nozzle and further support the statistical results indicating improved dimensional accuracy with smaller nozzle diameters.

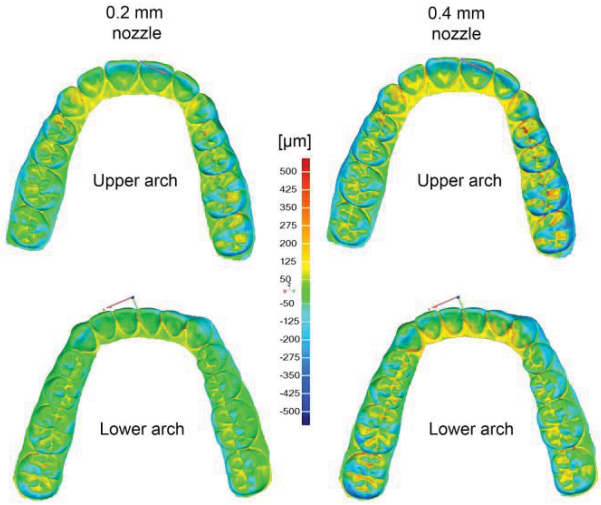

Figure 5. Color-coded deviation maps obtained from the 3D comparison analysis between the printed models and the reference STL datasets. Maxillary and mandibular arches printed with the 0.2 mm and 0.4 mm nozzles are presented. The color scale represents point-to-surface deviations in micrometers (µm), with warm colors indicating positive deviations and cool colors indicating negative deviations

Overall, the results indicate that nozzle diameter represents the primary factor influencing the dimensional accuracy of FDM-printed dental models, while the anatomical morphology of the arch also contributes to the variability observed between maxillary and mandibular models.

DISCUSSIONS

The present study evaluated the influence of nozzle diameter and arch morphology on the dimensional accuracy of dental models manufactured through fused deposition modeling (FDM) using the Bambu Lab X1 Carbon system. The results indicate that nozzle diameter represents the main determinant of printing precision, as the 0.2 mm nozzle significantly improved the trueness of printed models compared with the standard 0.4 mm configuration. In addition, mandibular models exhibited greater dimensional stability than maxillary models, an observation that may be explained by differences in anatomical volume and surface geometry between the two arch types.

The 0.2 mm nozzle produced significantly lower RMS values across all experimental groups. This finding is consistent with previous studies by Khaw et al. [2], which reported that reducing nozzle diameter decreases the staircase effect on inclined surfaces and enables a more accurate reproduction of complex dental morphologies, including occlusal anatomy and interproximal regions. Although 0.4 mm nozzles are frequently preferred in clinical workflows because of faster fabrication times and a lower risk of clogging, they resulted in a mean RMS error of 128.6 ± 8.7 µm for maxillary models in the present study. This value exceeds the clinically acceptable threshold of approximately 100 µm commonly reported for orthodontic and prosthodontic study models. In contrast, models printed with the 0.2 mm nozzle showed RMS deviations between 85.7 and 93.0 µm, placing them within the clinically acceptable range for diagnostic and treatment planning applications.

Another important finding was the significantly higher dimensional accuracy of mandibular models compared with maxillary models ($p < 0.001$). This difference may be explained by the thermal behaviour of thermoplastic filaments during the cooling phase after deposition. Maxillary models typically present a larger cross-sectional area and include a solid palatal region, which results in a greater material volume and footprint. Consequently, more thermal energy accumulates during deposition, which may influence the dimensional stability of the printed structure. As reported by Park et al. [15], larger printed volumes in FDM systems may lead to increased shrinkage and warping due to uneven cooling gradients. The statistically significant interaction between nozzle diameter and arch type ($p = 0.0087$) supports this interpretation, as the 0.2 mm nozzle produced a more pronounced improvement for maxillary models. These results suggest that higher resolution extrusion may partially compensate for the geometric complexity and volumetric shrinkage associated with larger anatomical datasets.

The use of RMS deviation as the primary accuracy metric allowed a comprehensive evaluation of trueness and precision. Boxplot analysis showed that the 0.2 mm nozzle not only improved trueness but also increased measurement consistency, as indicated by the narrowest interquartile range in the mandibular group. This higher level of reproducibility is particularly relevant in clinical workflows, where the predictability of the additive manufacturing process is considered as important as the absolute dimensional accuracy of printed models [3]. Although a slight deviation from normality was observed in one experimental group, the balanced experimental design and the homogeneity of variances confirmed by Levene's test support the robustness of the applied two-way ANOVA.

Despite the clear accuracy advantages of the 0.2 mm nozzle, this configuration presents certain practical limitations. Smaller nozzle diameters increase printing time and may also raise the likelihood of nozzle obstruction, as previously reported by Mani et al. [16]. Consequently, the choice of nozzle diameter in clinical practice must balance dimensional accuracy with manufacturing efficiency. Overall, the findings of this study provide useful guidance for optimizing FDM parameters in digital dentistry and highlight that both hardware configuration and anatomical morphology should be considered to achieve optimal manufacturing outcomes.

The frequently cited threshold of approximately 100 μm RMS for dental model accuracy should be interpreted as a practical benchmark rather than a universally established clinical cutoff. International standards such as ISO 12836 [18] define methods for evaluating trueness and precision of digital dental devices, but do not prescribe specific clinical thresholds. In prosthodontic workflows, the 100 μm value is often justified by analogy with reported marginal gap tolerances and cement film thickness values of approximately 100–120 μm [19]. However, acceptable deviations vary depending on the clinical application. For example, orthodontic digital models and aligner-related discrepancies may reach 00.30 mm without affecting treatment planning [20]. In the present study, the RMS values obtained with the 0.2 mm nozzle (85.7–93.0 μm) fall within commonly cited accuracy targets for dental models, whereas the values observed with the 0.4 mm nozzle approach the upper range of these benchmarks.

It should be noted that the present investigation was conducted using a single FDM platform, namely the Bambu Lab X1 Carbon, operating within the proprietary Bambu Studio slicing environment. As a consequence, the dimensional accuracy values obtained in this study may be influenced by several machine-specific variables, including firmware-regulated extrusion dynamics, automated calibration procedures, motion control algorithms, and the proprietary slicing strategies implemented by the manufacturer. These factors can directly affect the stability of layer deposition, the control of extrusion width, and the thermal conditions governing material solidification during the printing process.

Therefore, although the observed relationship between nozzle diameter and the dimensional accuracy of the fabricated models is likely representative of general trends within FDM technology, the absolute root mean square (RMS) deviation values reported herein should be interpreted with caution, as they may differ when alternative printers, firmware architectures, or slicing software are employed. Future investigations incorporating multiple FDM systems and a broader range of printable materials would be beneficial in order to further validate the reproducibility and generalizability of these findings within digital dental manufacturing workflows.

The present study has several other limitations, as the experiments were performed using a single a single thermoplastic material, which may restrict the generalizability of the findings to other materials commonly used in FDM printing. In addition, dimensional accuracy was evaluated through surface-based deviation analysis using RMS values derived from digital model comparison. Although this approach reflects geometric trueness, it does not directly assess the clinical fit of fabricated appliances. Potential sources of manufacturing error related to toolpath generation and G-code execution, previously reported in additive manufacturing research such as the work of Beyer et al. [17], were also not investigated. Finally, only two nozzle diameters were included, and future studies should examine a wider range of extrusion parameters and printing platforms to further optimize FDM workflows for dental model fabrication.

CONCLUSIONS

Within the limitations of this study, nozzle diameter significantly influenced the dimensional accuracy of dental models produced through fused deposition modelling. Models printed with the 0.2 mm nozzle exhibited significantly lower RMS deviations and improved trueness compared with those fabricated using the 0.4 mm nozzle. In addition, mandibular models demonstrated greater dimensional stability than maxillary models, likely due to differences in anatomical geometry and material distribution during the printing and cooling process. These findings indicate that the use of smaller nozzle diameters may improve the curacy of FDM printed dental models, particularly in situations where high precision is required for diagnostic or orthodontic applications.

Funding

This research was funded by the National Recovery and Resilience Plan (PNRR), project PNRRIII-C9-2023-I8 “Technologically Enabled Advancements in Dental Medicine (TEAM)”, Contract No. CF 80/31.07.2023, Project No. 760235/28.12.2023.

Acknowledgments

This study was supported by project PNRRIII-C9-2023-I8, "Technologically Enabled Advancements in Dental Medicine (TEAM)", CF. 80/31.07.2023, number 760235/28.12.2023. The authors used ChatGPT, an AI language model developed by OpenAI, exclusively to improve the manuscript’s language and readability. All the scientific content, interpretations, and conclusions are the original work of the authors.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, M.C.M. and A.V.B.; Methodology, M.C.M., A.V.B. and A.G.; Software, M.C.M.; Validation, M.C.M., A.V.B. and M.H.; Formal analysis, M.C.M. and A.V.B.;

Investigation, M.C.M. and A.G.; Resources, M.H. and C.S.; Data curation, M.C.M. and A.V.B.; Writing—original draft preparation, M.C.M. and A.V.B.; Writing—review and editing, A.V.B., M.H. and C.S.; Visualization, M.C.M.; Supervision, A.V.B. and C.S.; Project administration, A.V.B. All authors have read and agreed to the published version of the manuscript.

Ethics Statement

This study was conducted in vitro and did not involve human participants, human-derived materials, or animal subjects. Therefore, ethical approval was not required.

REFERENCES

[1] Etemad-Shahidi Y, Qallandar OB, Evenden J, Alifui-Segbaya F, Ahmed KE. Accuracy of 3-dimensionally printed full-arch dental models: a systematic review. J Clin Med. 2020;9(10):3357.

[2] Khaw S, Liu X, Cameron A, Aarts J, Choi JJE. Factors influencing the dimensional accuracy of additively manufactured dental models: A systematic review of in vitro studies. J Mech Behav Biomed Mater. 2023;146:106057.

[3] Kim SY, Shin YS, Jung HD, Hwang CJ, Baik HS, Cha JY. Precision and trueness of dental models manufactured with different 3-dimensional printing techniques. Am J Orthod Dentofacial Orthop. 2018 Jan;153(1):144–53.

[4] Beyer M, Scheller L, Burde AV, Abazi S, Sommacal A, Seifert L, Sharma N, Thieringer FM. Comparative evaluation of sla and dlp 3d printing in dental implant guides: impact on fabrication accuracy, speed, and resin usage. Dent J. 2025;13(10):471.

[5] Alharbi N, Wismeijer D, Osman R. Additive manufacturing techniques in prosthodontics: where do we currently stand? A critical review. Int J Prosthodont. 2017;30(5):474–84.

[6] Jeong M, Radomski K, Lopez D, Liu JT, Lee JD, Lee SJ. Materials and applications of 3d printing technology in dentistry: an overview. Dent J. 2023;12(1):1.

[7] Borthakur PP, Sahariah JJ, Sarma M, Das A, Pathak K, Ahmad MZ, et al. Advances in 3D printing for dentistry: clinical applications and future perspectives. Explor Med. 2025;6:1001374.

[8] Ben Said L, Ayadi B, Alharbi S, Dammak F. Recent advances in additive manufacturing: a review of current developments and future directions. Machines. 2025; 13(9):813.

[9] Batu T, Lemu HG, Shimels HG, Zebenay M. Process parameter modelling and optimization techniques applied to fused deposition modelling: A review. IOP Conf Ser Mater Sci Eng. 2023;1294(1):012047.

[10] Chen Y, Wei J. Application of 3D Printing Technology in Dentistry: A Review. Polymers. 2025;17(7):886.

[11] Birgani PT, Hardani H. Effect of nozzle diameter on mechanical properties and microstructure of fused deposition modeling 3D printed polylactic acid parts. ResearchSquare [Preprint]. 2025.

[12] Ferretti P, Leon-Cardenas C, Santi GM, Sali M, Ciotti E, Frizziero L, et al. Relationship between FDM 3D printing parameters study: parameter optimization for lower defects. Polymers. 2021;13(13):2190.

[13] Tayyab M, Tanveer MQ, Singari RM, Sathikh PM. Effect of nozzle diameter on the physical behavior of fdm-printed part: an experimental study. In: Yadav S, Shrivastava Y, Rab S, editors. Recent Advances in mechanical engineering. Singapore: Springer Nature Singapore; 2024. p. 489–500.

[14] Czyżewski P, Marciniak D, Nowinka B, Borowiak M, Bieliński M. Influence of extruder's nozzle diameter on the improvement of functional properties of 3d-printed pla products. Polymers. 2022;14(2):356.

[15] Park ME, Shin SY. Three-dimensional comparative study on the accuracy and reproducibility of dental casts fabricated by 3D printers. J Prosthet Dent. 2018;119(5):861.e1-e7.

[16] Mani M, Karthikeyan AG, Kalaiselvan K, Muthusamy P, Muruganandhan P. Optimization of FDM 3-D printer process parameters for surface roughness and mechanical properties using PLA material. Mater Today Proc. 2022;66:1926–31.

[17] Beyer M, Burde A, Roser AE, Beyer M, Abazi S, Thieringer FM. A Slicer-Independent Framework for Measuring G-Code Accuracy in Medical 3D Printing. J Imaging. 2026;12(1):25.
[18] ISO 20896-1:2019. Dentistry — Digital impression devices — Part 1: Methods for assessing accuracy. Geneva: International Organization for Standardization; 2019.
[19] Son K, Lee KB. Effect of Tooth Types on the Accuracy of Dental 3D Scanners: An In Vitro Study. Materials (Basel). 2020;13(7):1744.
[20] Hiroki Y, Sohmura T, Satoh H, Takahashi J, Takada K. Complete 3-D reconstruction of dental cast shape using perceptual grouping. IEEE Trans. Med. Imaging. 2001;20(10): 1093–1101.