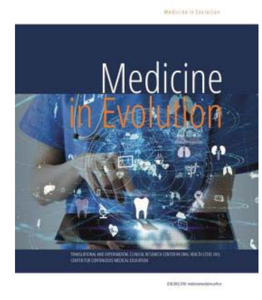
Dimensional Accuracy of Dental Models Printed with Different Resins Using a Low-Cost LCD 3D Printer



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Abstract

This in vitro study investigated the influence of resin formulation on the dimensional accuracy of dental models fabricated using a consumer-grade LCD 3D printer. Thirty full-arch models (n = 10 per group) were printed with three resins: Water-Washable, Ortho Model, and Study Model. All specimens were produced at 50 µm layer height and analyzed using an inEos X5 scanner and Geomagic Control 2014 software. Trueness was quantified using Root Mean Square (RMS) deviation values. One-way ANOVA revealed a significant effect of resin type ($F(2,27) = 9.53$, $p = 0.0007$). The water-washable resin showed the lowest mean RMS deviation (109.0 ± 13.8 µm). All materials remained within clinically acceptable limits (<250 µm). Resin selection influences accuracy when using consumer-grade LCD printing systems.

Keywords: 3D printing, Digital dentistry, Dental resins, Dimensional accuracy, Vat polymerization, LCD 3D printer, Digital workflow

INTRODUCTION

Vat photopolymerization (VP) is extensively employed in digital dentistry for fabricating dental models and appliances [1–3]. Among VP technologies, liquid crystal display printers solidify photopolymer resins layer-by-layer through a UV light source modulated by an LCD mask [4]. Relative to stereolithography and digital light processing printers, LCD systems deliver cost-effective performance alongside high pixel resolution and satisfactory surface finish [5].

The rapid development of consumer-grade LCD printers has led to their increasing adoption in dental practices and academic settings. These devices enable affordable in-office manufacturing and streamlined digital workflows [6]. However, despite improvements in screen resolution and light uniformity, concerns remain regarding the dimensional reliability of models produced with consumer-grade systems [7].

Dimensional accuracy is critical in dentistry, as printed models frequently serve as the basis for prosthetic restorations, orthodontic appliances, and surgical guides [8]. According to ISO standards, accuracy includes trueness and precision [9]. In vat photopolymerization systems, factors such as light distribution, exposure parameters, peel forces [10], and post-curing conditions can influence accuracy [11]. Among these variables, resin composition plays a central role. Differences in polymerization kinetics and volumetric shrinkage may affect the dimensional stability of printed objects, particularly in systems where exposure conditions are optimized for general rather than material-specific performance [12].

Although previous studies have evaluated the accuracy of professional-grade systems [13], limited evidence exists regarding resin-dependent differences when using consumer-grade LCD printers. Given the expanding clinical use of these devices, understanding how resin selection influences dimensional accuracy is important for optimizing digital workflows.

The chemical composition of photopolymer resins should be regarded as an additional determinant of dimensional accuracy in vat photopolymerization systems, alongside printer architecture and exposure-related parameters [14]. Dental printing resins are generally formulated from multifunctional methacrylate monomers and oligomers, in association with photoinitiators and auxiliary additives intended to modulate viscosity, polymerization kinetics, and the final mechanical behavior of the material. Variations in resin formulation may alter the extent of polymerization shrinkage, the resulting cross-link density, and the magnitude of internal stresses generated during sequential layer curing [15]. As a consequence, even under identical hardware settings and slicing conditions, distinct resin systems may yield different levels of dimensional trueness.

From a clinical perspective, faithful reproduction of dental anatomy remains essential for the predictability of digital workflows [16]. In orthodontics, printed models are routinely employed for treatment planning and for the fabrication of thermoformed aligners, in which even limited geometric discrepancies may influence appliance fit and the pattern of force delivery [17]. In prosthodontics and implant dentistry, inaccuracies at the model level may compromise diagnostic assessment and may further propagate through subsequent digital and laboratory stages, resulting in cumulative error [18]. Accordingly, the assessment of dimensional behavior in commonly used dental resins represents a necessary step toward the optimization of additive manufacturing workflows in dental practice. Similar concerns regarding the clinical relevance of accuracy have been emphasized in previous investigations on digital scanning and additively manufactured dental models.

Despite the growing adoption of consumer-grade LCD-based printers into dental laboratories, comparative evidence specifically addressing the effect of resin formulation on dimensional accuracy remains limited. Most currently available studies have concentrated predominantly on printer technology [19], layer thickness [20], or post-processing conditions [21], whereas the independent contribution of material chemistry has been explored to a lesser extent. Existing work from the same field has already shown that printer type and additive manufacturing method can significantly influence the dimensional outcome of dental models [22], thereby supporting the need to isolate and investigate the resin-related component more rigorously.

Therefore, the aim of this in vitro study was to evaluate the dimensional accuracy of dental models printed with three different resins using a consumer-grade LCD 3D printer. The null hypothesis was that resin type would not significantly influence root mean square (RMS) deviation values.

Aim and objectives

The aim of this in vitro study was to evaluate the dimensional accuracy of dental models fabricated with three different resin formulations using a consumer-grade LCD 3D printer. RMS deviation values were calculated to assess trueness relative to reference STL files, and differences among resin types were compared under standardized printing and post-processing conditions. Additionally, the study aimed to determine whether all printed models remained within clinically acceptable deviation thresholds (<250 µm).

MATERIAL AND METHODS

This in vitro experimental study was designed to evaluate the influence of resin formulation on the dimensional accuracy of dental models fabricated using a consumer-grade Liquid Crystal Display (LCD) vat photopolymerization system.

A standardized reference dataset consisting of one ideal full-arch dental model in Standard Tessellation Language (STL) format was selected as the control geometry. The reference digital model was designed as hollow structure with a uniform wall thickness of 2.5 mm to optimize material consumption while maintaining mechanical stability. The same digital reference file was used for all specimens to ensure methodological standardization. A total of 30 models were fabricated and allocated into three experimental groups according to resin type (n = 10 per group): Water-Washable Dental Model Resin (WW), Dental Ortho Model Resin (OM), and Dental Study Model Resin (DS) (Phrozen Tech Co., Hsinchu City, Taiwan). All resins were manufactured by the same company as the printing system to minimize variability related to hardware–material compatibility.

Additive manufacturing was performed using a Phrozen Sonic Mini 8K S (Phrozen Tech Co., Hsinchu City, Taiwan), a consumer-grade LCD-based system equipped with an 8K monochrome display (7500 × 3240-pixel resolution). The printer operates using a 405 nm ultraviolet light source and provides an approximate native XY resolution of 22 µm, enabling high-detail reproduction of dental geometries. Prior to fabrication, the printer was calibrated according to the manufacturer's recommendations to ensure consistent platform leveling and exposure conditions.

All models were printed at a standardized layer height of 50 µm and identical horizontal build orientation. STL files were prepared using Chitubox Basic version 2.3 software. Mesh integrity was verified prior to slicing, and automatic support generation was applied uniformly across all specimens. Printing parameters specific to each resin are summarized in Table 1.

Table 1. Printing parameters for each resin group

Parameter	**Water-Washable Resin (WW)**	**Ortho Model Resin (DO)**	**Study Model Resin (DS)**
Layer height	50 µm	50 µm	50 µm
Bottom layers	6	6	6
Bottom exposure time	20 s	30 s	25 s
Normal exposure time	4.7 s	6.9 s	4.2 s
Light-off delay	2 s	2 s	2 s
Lift height	3 mm	3 mm	3 mm
Lift speed	60 mm/min	60 mm/min	50 mm/min
Anti-aliasing	Level 4	Level 4	Level 4
Shrinkage compensation (X/Y)	100.028% / 100.18%	100.042% / 100.06%	100.031% / 100.12%

The printing environment was maintained under standard laboratory conditions with an ambient temperature of approximately 22–24 °C. For each type of resin a brand new resin vat and build platform were used throughout the fabrication process, and the resin was gently mixed before each printing cycle to ensure homogeneous photopolymer composition.

Post-processing was performed according to the manufacturer's recommendations for each resin. For the Water-Washable Dental Model resin, printed objects were cleaned in an ultrasonic cleaner using clean water for 5 minutes to remove uncured resin, followed by drying in a dark environment for up to 30 minutes or immediate drying using compressed air; rubbing was avoided to prevent dimensional alteration. For the Dental Ortho Model and Dental Study Model resins, printed objects were cleaned in an ultrasonic cleaner using 95% isopropyl alcohol for 120 seconds, followed by drying under identical conditions; mechanical rubbing was avoided to preserve precision tolerances. Post-curing for all specimens was performed using a Phrozen Cure V2 unit (Phrozen Tech Co., Hsinchu City, Taiwan). Water-Washable and Ortho Model specimens were cured for 30 minutes, whereas Study Model specimens were cured for 1 minute, in accordance with manufacturer instructions.

In order to evaluate the dimensional accuracy of the resulting models, all printed models were digitized using an inEos X5 laboratory scanner (Dentsply Sirona, Bensheim, Germany). Each model was scanned under standardized acquisition settings and exported in STL format for metrological analysis.

Three-dimensional metrological evaluation was conducted using Geomagic Control 2014 software (3D Systems, Rock Hill, USA). Each scanned STL dataset was superimposed onto its corresponding reference file using a staged best-fit alignment protocol, comprising an initial alignment with 300 common points, followed by refinement with 3000 points and a final high-precision alignment using 15000 points. Surface deviation analysis was subsequently performed using the "3D Compare" module to generate color-coded deviation maps and calculate Root Mean Square (RMS) deviation values.

Statistical analysis was performed using Python (SciPy and Statsmodels libraries). Data normality was assessed using the Shapiro–Wilk test, and homogeneity of variances was evaluated using Levene's test. As assumptions were satisfied, intergroup comparisons were conducted using one-way analysis of variance (ANOVA), followed by Tukey's post-hoc testing. Effect sizes were calculated using eta-squared (η^2) and omega-squared (ω^2). Statistical significance was set at $\alpha = 0.05$.

RESULTS

A total of 30 full-arch dental models (n=10 per resin type) were successfully fabricated, post-processed, digitized, and subjected to rigorous three-dimensional surface deviation analysis. Notably, zero printing failures, structural fractures, or scanning artifacts occurred, ensuring no specimens required exclusion and confirming the reliability of the methodology across all groups. Descriptive statistics for RMS deviation values are presented in Table 2.

Table 2. Printing parameters for each resin group

Resin	Mean ± SD (µm)	Median (µm)	IQR (µm)	Min–Max (µm)	95% CI (µm)
Water-Washable Resin (WW)	109.0 ± 13.8	108.5	25.8	91-126	99.1–118.9
Study Model Resin (DS)	124 ± 8.1	125.1	10.8	110-136	118.2-129.8
Ortho Model Resin (DO)	131 ± 11.9	130.9	19.0	112-148	122.5-139.5

The WW resin demonstrated the lowest mean RMS deviation, demonstrating superior dimensional trueness under the standardized printing conditions employed in this study. In contrast, the Study Model Resin exhibited intermediate mean RMS values with the lowest dispersion, while the Ortho Model Resin produced the highest mean RMS deviation coupled with greater variability, as demonstrated in Figure 1.

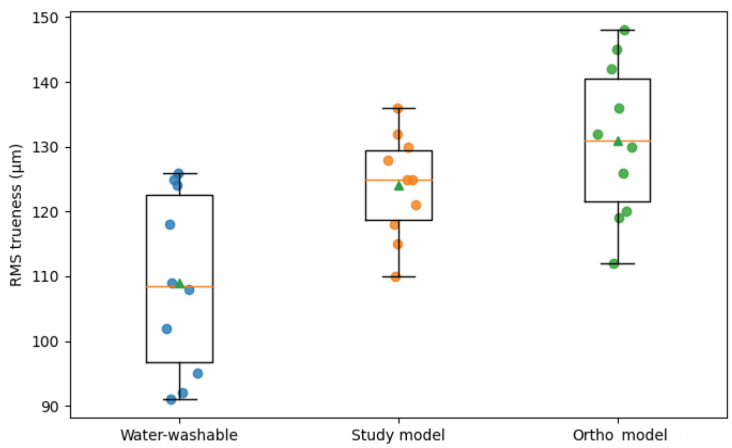

Figure 1. Comparison of RMS trueness among the three resin groups

Assessment of normality was performed using the Shapiro–Wilk test for each resin group. No statistically significant deviations from normal distribution were detected ($p > 0.05$ for all groups), indicating that the assumption of normality was satisfied. Visual inspection of the corresponding Q–Q plots (Figure 2) demonstrated that data points closely followed the theoretical reference line, with only minor deviations at the distribution tails, further supporting approximate normality of RMS values.

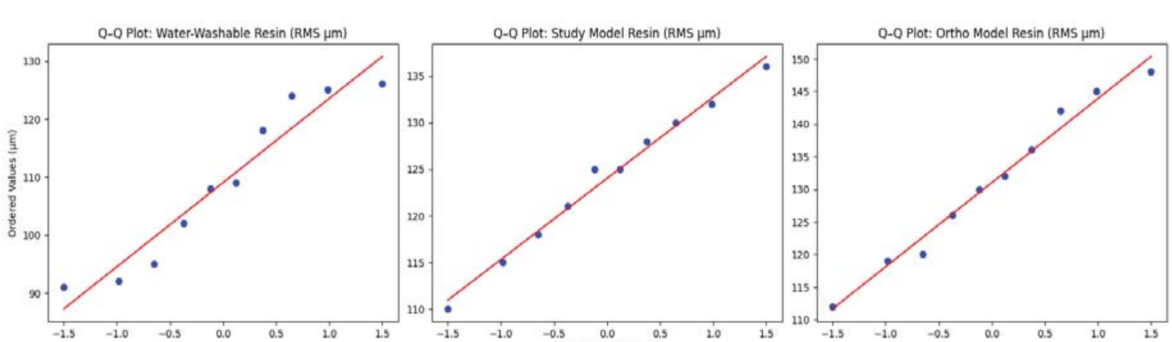

Figure 2. Q–Q plots illustrating the distribution of RMS deviation values for each resin group

Homogeneity of variances was evaluated using Levene's test, which did not reveal significant differences in variance among groups (p = 0.167). These findings confirmed that the assumptions required for parametric one-way ANOVA were met.

One-way ANOVA demonstrated a statistically significant effect of resin type on dimensional trueness (F (2,27) = 9.53, p = 0.0007), indicating that mean RMS values differed among the evaluated materials. The magnitude of this effect was substantial, as reflected by a large effect size (η^2 = 0.41; ω^2 = 0.36). These values indicate that approximately 41% of the total variability in RMS deviation measurements can be attributed to differences in resin formulation rather than random variation.

Post-hoc Tukey analysis revealed that the Water-Washable Resin exhibited significantly lower RMS values compared with the Ortho Model Resin (mean difference 22 µm; p = 0.0006) and the Study Model Resin (mean difference 15 µm; p = 0.0188). No statistically significant difference was identified between the Ortho and Study Model resins (p = 0.376).

Representative three-dimensional color-coded deviation maps were generated for each resin group to illustrate the spatial distribution of surface discrepancies relative to the reference model, as seen in Figure 3.

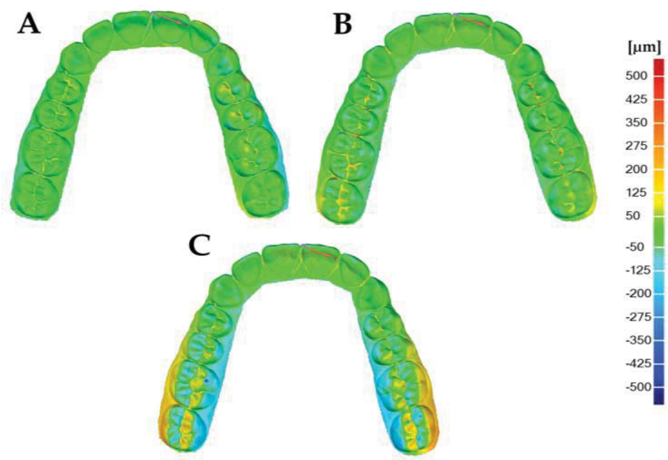

Figure 3. Representative color-coded deviation maps illustrating three-dimensional surface discrepancies relative to the reference STL model. (A) Water-Washable Dental Model Resin; (B) Study Model Resin; (C) Ortho Model Resin

All groups predominantly showed green areas within the predefined tolerance range; however, localized deviations were more evident in the Study and Ortho Model resins compared with the more homogeneous pattern observed in the Water-Washable group.

DISCUSSIONS

The present in-vitro study evaluated the influence of resin formulation on the dimensional accuracy of dental models fabricated using a consumer-grade LCD vat photopolymerization system. The results demonstrated that resin type significantly affected RMS trueness values, leading to rejection of the null hypothesis. Although all tested materials produced models within clinically acceptable limits (<250 µm) [23], statistically significant differences were observed among groups.

The Water-Washable Dental Model Resin exhibited the lowest mean RMS deviation, followed by the Study Model Resin, while the Ortho Model Resin demonstrated the highest deviations. The magnitude of the effect (η^2 = 0.41) indicates that resin formulation accounted for a substantial proportion of the observed variability. These findings suggest that, even when using the same printer, identical build orientation, standardized layer thickness (50 µm), and manufacturer-matched materials, resin chemistry remains a decisive factor influencing dimensional trueness.

In vat photopolymerization systems, dimensional deviations are primarily influenced by polymerization shrinkage, light scattering behavior, and interlayer curing dynamics [24,25]. Differences in monomer composition, cross-link density, viscosity, and photoinitiator systems affect polymerization kinetics and volumetric contraction during curing [26]. Resins with faster polymerization rates or higher cross-link density may generate increased internal stresses, potentially contributing to distortion. Conversely, formulations optimized for dimensional stability may exhibit reduced shrinkage and more uniform curing behavior [27]. The superior performance of the water-washable resin under the present conditions may be attributed to differences in shrinkage compensation and polymer network formation during layer-by-layer curing.

It is also important to consider the interaction between exposure parameters and resin formulation. Although layer height and printer hardware were standardized, normal exposure times differed between groups according to manufacturer-recommended profiles. Longer exposure times, such as those used for the Ortho Model Resin, may increase overcuring at layer interfaces, potentially affecting dimensional fidelity. In consumer-grade LCD systems, where exposure calibration is less dynamically regulated than in medical-grade 3D printers, such material–parameter interactions may become more pronounced.

Despite statistically significant differences, all groups remained well below the commonly accepted clinical threshold of 250 µm for dental model fabrication. From a clinical perspective, the magnitude of intergroup differences (15–22 µm) may be considered modest; however, in workflows requiring high precision, such as fixed prosthodontics, small deviations can accumulate across digital steps. Therefore, resin selection may represent a relevant optimization parameter in digital dental workflows.

The present findings align with previous investigations reporting that material-dependent factors influence the accuracy of additively manufactured dental models. While many studies focus primarily on printer technology or layer thickness, the current results emphasize that material formulation alone can significantly affect trueness outcomes, within the same manufacturer ecosystem.

Several limitations must be acknowledged. First, the study evaluated only trueness (RMS deviation) and did not assess precision through repeated-print variability analysis. Second, only one printer model and one set of exposure parameters per resin were investigated. Third, environmental factors such as ambient temperature and resin aging were not systematically controlled beyond standard laboratory conditions.

In addition, it should be acknowledged that the present investigation was conducted using a single consumer-grade LCD printer platform. In vat photopolymerization systems, dimensional accuracy may also be affected by hardware-specific variables, including pixel size, light distribution across the LCD panel, peel mechanics during layer separation, and firmware-controlled exposure strategies [28]. Therefore, although the present findings emphasize the role of resin formulation, the absolute RMS values reported in this study should not be interpreted as universally transferable to all printing systems, as different printer architectures, light sources, and slicing environments may yield different outcomes.

Another factor that may influence dimensional behavior is the post-processing workflow. Cleaning procedures, solvent interaction, and post-curing protocols may alter the final degree of polymerization and, consequently, introduce additional dimensional changes [11]. In the present study, standardized cleaning and post-curing procedures were applied to all specimens in an attempt to minimize procedural variability. Nevertheless, differences in post-processing conditions may affect the dimensional stability of photopolymer materials and should be taken into account when comparing findings across studies.

From a clinical perspective, the results of the present study support the use of consumer-grade LCD printers for the fabrication of dental models intended for diagnostic and orthodontic applications. All tested resins produced deviations well below the 250 µm threshold frequently regarded as clinically acceptable for dental models [29]. Such a level of accuracy is generally adequate for applications including study casts, orthodontic appliance planning, and thermoforming procedures. However, in workflows that demand a higher level of precision, such as the fabrication of prosthodontic restorations or implant-supported frameworks, cumulative errors arising along the digital chain may become clinically relevant. In these situations, optimization of both material selection and printing parameters becomes particularly important.

It should also be noted that the present analysis was conducted using a single model geometry and a limited number of specimens per group. Although the standardized model allows controlled comparison between materials, it may not fully reproduce the geometric complexity encountered in clinical dental arches. More complex anatomical structures may present additional challenges related to support placement, layer orientation, and localized polymerization behavior.

Future research should further investigate the interaction between resin formulation, exposure parameters, and printer architecture in order to clarify the mechanisms underlying dimensional deviations in LCD vat photopolymerization systems. Studies involving multiple printer platforms, larger sample sizes, and repeated-print precision analyses would provide a more comprehensive understanding of the reproducibility and generalizability of these findings within clinical digital dentistry workflows.

CONCLUSIONS

Within the limitations of this in vitro study, resin formulation significantly influenced the dimensional accuracy of dental models printed using a consumer-grade LCD 3D printer. Although all materials achieved clinically acceptable trueness, the water-washable resin demonstrated superior dimensional performance under standardized conditions. These findings highlight the importance of material selection when implementing consumer-grade vat photopolymerization systems in the digital dental workflow.

Conflicts of Interest

The authors declare no conflict of interest.

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