



BASIC RESEARCH:

Dimensional Accuracy of Additively Manufactured Dental Models Compared with Conventional Gypsum Casts Across Different Measurement Spans: An *In Vitro* Study

Exactitud dimensional de modelos dentales fabricados mediante manufactura aditiva en comparación con modelos convencionales de yeso en diferentes distancias de medición: un estudio *in vitro*

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Received: 4-V-2026

Accepted: 3-VI-2026

ABSTRACT: Accurate dental models are critical for achieving predictable outcomes in prosthodontics; however, the transition from conventional to digital workflows raises concerns regarding dimensional reliability across different clinical scenarios. This *in vitro* study evaluated the dimensional accuracy of conventional gypsum casts and additively manufactured dental models using standardized linear measurements derived from a metal master reference model, with particular emphasis on span-dependent behavior. Twenty definitive models were divided into 2 groups (n=10): gypsum casts obtained from addition silicone impressions and resin models fabricated through intraoral scanning followed by LCD-based 3-dimensional printing. Ten predefined linear distances were measured using a digital Vernier caliper (± 0.01 mm), and deviations were calculated relative to the reference model. Statistical analysis included Shapiro–Wilk testing and independent t tests or Mann–Whitney U tests ($\alpha=.05$). Gypsum casts demonstrated significantly smaller deviations in localized measurements (0.05–0.12 mm) compared with additively manufactured models (0.22–0.44 mm) ($P<.05$). For inter-point distances, both workflows showed comparable performance in selected spans, whereas differences became evident in longer transverse measurements. No significant differences were observed in diagonal dimensions. Dimensional discrepancies were not uniformly distributed, indicating that measurement span influences

accuracy outcomes. Within the limitations of this study, gypsum casts remain more precise for short-span measurements, while additively manufactured models provide comparable accuracy over broader distances. Both workflows produced deviations within clinically acceptable ranges, supporting the use of additively manufactured models as a reliable alternative in digital prosthodontic workflows, particularly when full-arch spatial relationships are prioritized.

KEYWORDS: Models, Dental; Printing, Three-Dimensional; Imaging, Three-Dimensional; Computer-Aided Design; Dental Impression Materials; Prosthodontics.

RESUMEN: Los modelos dentales precisos son fundamentales para lograr resultados predecibles en prostodoncia; sin embargo, la transición a flujos digitales genera dudas sobre su fiabilidad dimensional en distintos escenarios clínicos. Este estudio *in vitro* evaluó la exactitud dimensional de modelos de yeso convencionales y modelos fabricados mediante manufactura aditiva utilizando mediciones lineales estandarizadas derivadas de un modelo maestro metálico de referencia, con énfasis en el comportamiento según la extensión de medición. Se analizaron veinte modelos (n=10 por grupo): modelos de yeso obtenidos de impresiones con silicona por adición y modelos de resina obtenidos mediante escaneo intraoral seguido de impresión 3D con tecnología LCD. Se registraron diez distancias lineales con un calibrador digital (± 0.01 mm), y las desviaciones se calcularon respecto al modelo de referencia. El análisis estadístico incluyó la prueba de Shapiro–Wilk y pruebas t o U de Mann–Whitney ($\alpha=.05$). Los modelos de yeso mostraron menores desviaciones en mediciones localizadas (0.05-0.12 mm) frente a los modelos impresos (0.22-0.44 mm) ($P<.05$). En distancias interpuntuales, ambos métodos mostraron resultados comparables en algunos tramos, mientras que se evidenciaron diferencias en mediciones transversales mayores. No hubo diferencias significativas en mediciones diagonales. Las discrepancias no fueron uniformes, lo que indica que la extensión de medición influye en la exactitud. Dentro de las limitaciones del estudio, los modelos de yeso son más precisos en distancias cortas, mientras que los modelos impresos ofrecen resultados comparables en distancias mayores. Ambos métodos presentaron desviaciones clínicamente aceptables, lo que respalda el uso de modelos impresos en flujos digitales, especialmente en análisis de arcada completa.

PALABRAS CLAVE: Modelos Dentales; Impresión Tridimensional; Exactitud de las Mediciones; Diseño Asistido por Computadora; Materiales de Impresión Dental; Prostodoncia.

INTRODUCTION

Accurate dental models are essential in prosthodontics because they support diagnosis, treatment planning, occlusal analysis, and fabrication of indirect restorations. Dimensional inaccuracies may affect marginal adaptation, interarch relationships, and spatial reproduction of dental anatomy, thereby influencing restorative precision (1,2).

Conventional gypsum casts obtained from elastomeric impressions remain the reference standard because of their ability to reproduce fine detail with acceptable dimensional stability (3). However, conventional workflows are susceptible to distortion related to impression shrinkage, stone expansion, handling variability, fracture risk, and storage requirements. These limitations may reduce reproducibility and workflow efficiency (4).

Digital dentistry has introduced alternative workflows based on intraoral scanning and additive manufacturing, enabling physical model fabrication directly from digital datasets. These approaches facilitate digital storage, rapid reproduction, and integration with CAD-CAM systems (2,4-6). Consequently, additively manufactured dental models are increasingly incorporated into prosthodontic workflows.

Despite these advantages, dimensional accuracy remains a critical concern because deviations may arise during scanning, printing, and postprocessing procedures (7-9). Previous studies have shown that printing technology, layer thickness, build orientation, resin properties, and postpolymerization protocols can influence dimensional outcomes (10-14). In addition, variability has been reported among different additive manufacturing technologies, including liquid crystal display (LCD), digital light processing (DLP), and stereolithography (SLA) (12,15-17).

Dimensional deviations may not occur uniformly across the dental arch. Larger measurement spans and full-arch configurations have been associated with increased distortion compared with localized regions (3,18). Therefore, evaluation based solely on global accuracy metrics may overlook clinically relevant dimensional variation.

Most previous investigations have emphasized global trueness or three-dimensional superimposition methods. However, limited evidence exists regarding how dimensional deviations behave across different measurement spans when evaluated using standardized linear reference geometry. Understanding this span-dependent behavior may provide clinically relevant insight into localized versus extended dimensional distortion patterns. Therefore, the purpose of this *in vitro* study was to compare the dimensional accuracy of conventional gypsum casts and additively manufactured dental models using predefined linear measure-

ments derived from a standardized metal master reference model.

MATERIALS AND METHODS

STUDY DESIGN AND SAMPLE SIZE CALCULATION

This *in vitro* study evaluated the dimensional accuracy of dental models fabricated using 2 workflows: conventional gypsum casts obtained from elastomeric impressions and additively manufactured resin models generated from a digital workflow. Twenty definitive models were produced and divided into 2 groups ($n=10$ per group). Sample size calculation was performed using G*Power software (version 3.1; Heinrich Heine University, Düsseldorf, Germany). Based on pilot measurements, an effect size (d) of 1.20, $\alpha=.05$, and statistical power of 80%, a minimum of 8 specimens per group was required. Ten specimens per group were included to increase robustness and compensate for potential variability. A standardized metal master reference model served as the dimensional control. Therefore, no additional control group was included because both workflows were directly compared with the master reference model.

MASTER REFERENCE MODEL AND CONVENTIONAL WORKFLOW

The master reference model had a horseshoe-shaped configuration with four equidistant square reference prominences (7×7 mm), labeled A-D, positioned symmetrically to permit standardized linear measurements in longitudinal, transverse, and diagonal directions (Figure 1.A,B). The 7×7 -mm dimensions were selected to provide standardized and reproducible reference landmarks for linear measurements. For the conventional workflow, 10 impressions were obtained using an addition silicone material with a heavy-body and light-body technique (Zhermack, Badia Polesine, Italy), according to manufacturer instructions.

Impressions were inspected for defects and poured with type IV dental stone (Elite Rock; Zhermack) mixed according to the recommended powder-to-water ratio. After setting, casts were separated and stored at room temperature until analysis (3) (Figure 2.A).

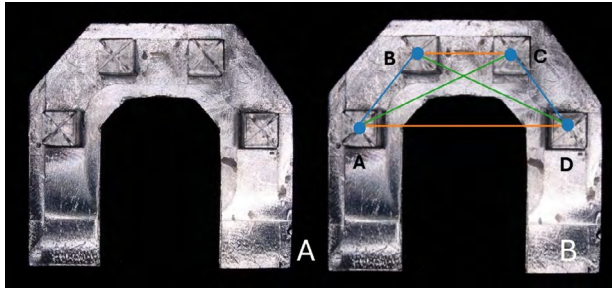


Figure 1. Metal master reference model used as dimensional control. (A) Metal model with four equidistant square reference points (A-D). (B) Reference point configuration and linear measurement scheme used for dimensional evaluation.

DIGITAL WORKFLOW AND ADDITIVE MANUFACTURING

For the digital workflow, the master model was digitized using an intraoral scanner (TRIOS 3; 3Shape A/S, Copenhagen, Denmark; software version 1.6.4), with a reported trueness of approximately 20-30 μm under controlled *in vitro* conditions. Ten scans were obtained using a standardized scanning path, and files were exported in STL format (1,19-21). Additively manufactured models were fabricated using an LCD 3-dimensional printer (Phrozen Sonic XL 4K; Phrozen Technology Corp., Taiwan) with identical printing parameters, including a 50- μm layer thickness, horizontal build orientation (0 degrees), and 2.5-second exposure time per layer (4,16). After printing, specimens

underwent standardized postprocessing consisting of two sequential washes in isopropyl alcohol for 5 minutes each, air drying, and ultraviolet postpolymerization for 15 minutes (Phrozen Cure Unit; Phrozen Technology Corp.) (10,13) (Figure 2.B).

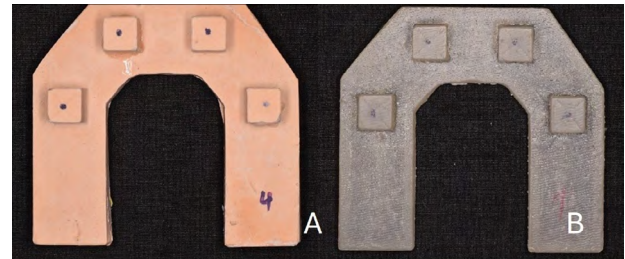


Figure 2. Representative models fabricated with the evaluated techniques. (A) Conventional gypsum cast obtained from an elastomeric impression. (B) Additively manufactured resin model obtained from digital scanning and three-dimensional printing workflow.

DIMENSIONAL MEASUREMENTS AND RELIABILITY ASSESSMENT

Measurement order was randomized using a computer-generated sequence, and the operator responsible for measurements was blinded to group allocation. Dimensional accuracy was assessed using predefined linear distances between reference points A-D. Ten measurements were recorded per specimen: single-point (M1-M4), transverse (M5-M8), and diagonal (M9-M10). Linear measurements were selected to evaluate dimensional behavior across different spans and identify localized and extended distortion patterns. All measurements were obtained using a digital Vernier caliper (Absolute Digimatic; Mitutoyo Corp., Kawasaki, Japan) with an accuracy of ± 0.01 mm. Each measurement was repeated three times by a calibrated operator, and the mean value was used

for analysis. Dimensional deviation was calculated as the absolute difference relative to the master reference model.

Intra-operator reliability was assessed by remeasuring 20% of specimens after a 7-day interval, and agreement was calculated using the intra-class correlation coefficient ($ICC > 0.90$).

STATISTICAL ANALYSIS

Statistical analysis was performed using SPSS Statistics v26 (IBM Corp., Armonk, NY, USA). Data normality was assessed using the Shapiro-Wilk test. Variables with normal distribution were analyzed using independent *t* tests, whereas non-normal variables were evaluated using Mann-Whitney *U* tests. Descriptive statistics included mean, standard deviation, absolute deviation, and 95% confidence intervals where applicable. Statistical significance was set at $\alpha = .05$.

RESULTS

Mean dimensional measurements and absolute deviations relative to the master reference model are presented in Table 1 and Table 2. Table 1 summarizes single-point measurements (M1-M4), whereas Table 2 reports inter-point measurements (M5-M10).

For single-point measurements, gypsum casts demonstrated consistently smaller deviations from the master reference model than additively manufactured models across all evaluated points. Gypsum deviations ranged from 0.05 to 0.12 mm, whereas additively manufactured models showed deviations ranging from 0.22 to 0.44 mm. Statis-

tically significant differences were observed for all single-point measurements ($P < .05$), indicating greater dimensional agreement of gypsum casts in localized regions.

For inter-point measurements, dimensional behavior varied according to measurement span. In transverse distances (M5-M8), both fabrication methods demonstrated comparable dimensional values in M5 and M6, with no statistically significant differences ($P > .05$). However, significant differences were identified for M7 and M8 ($P < .05$). Gypsum casts showed smaller deviations than additively manufactured models for M7 (0.60 mm versus 0.77 mm) and M8 (0.35 mm versus 0.65 mm).

For diagonal measurements (M9 and M10), both fabrication methods produced values close to the master reference model. Gypsum casts demonstrated deviations of 0.14 mm and 1.17 mm, whereas additively manufactured models showed deviations of 0.23 mm and 1.33 mm for M9 and M10, respectively. No statistically significant differences were identified between groups for these measurements ($P > .05$).

Overall, dimensional deviations varied according to measurement span rather than occurring uniformly across the evaluated model. Smaller discrepancies were observed in localized regions, whereas greater deviations occurred in selected inter-point spans, particularly for additively manufactured models. Most deviations remained within ranges considered clinically acceptable for prosthodontic model fabrication, despite differences observed between workflows and measurement spans.

Table 1. Single-point dimensional measurements and deviations relative to the master reference model (mm).

Measurement	Reference Point	Master (mm)	Gypsum (Mean $\pm$ SD)	AM Models (Mean $\pm$ SD)	Gypsum Deviation (mm)	AM Deviation (mm)	P-value
M1	A	8.17	8.23 $\pm$ 0.04	8.45 $\pm$ 0.07	0.06	0.28	0.002*
M2	B	8.00	8.12 $\pm$ 0.05	8.38 $\pm$ 0.06	0.12	0.38	<0.001*
M3	C	8.13	8.24 $\pm$ 0.06	8.57 $\pm$ 0.08	0.11	0.44	<0.001*
M4	D	8.27	8.32 $\pm$ 0.05	8.49 $\pm$ 0.07	0.05	0.22	0.004*

*Statistically significant difference ($P < .05$).

Values represent mean $\pm$ standard deviation.

Deviation values were calculated as the absolute difference relative to the master reference model.

Table 2. Inter-point dimensional measurements and deviations relative to the master reference model (mm).

Measurement	Reference Point	Master (mm)	Gypsum (Mean $\pm$ SD)	AM Models (Mean $\pm$ SD)	Gypsum Deviation (mm)	AM Deviation (mm)	P-value
M5	A-B	20.97	21.59 $\pm$ 0.10	21.48 $\pm$ 0.12	0.62	0.51	0.081
M6	B-C	20.30	21.38 $\pm$ 0.09	21.43 $\pm$ 0.11	1.08	1.13	0.214
M7	C-D	20.97	21.57 $\pm$ 0.08	21.74 $\pm$ 0.13	0.60	0.77	0.034*
M8	D-A	46.87	47.22 $\pm$ 0.15	47.52 $\pm$ 0.14	0.35	0.65	<0.001*
M9	A-C	38.21	38.35 $\pm$ 0.07	38.44 $\pm$ 0.09	0.14	0.23	0.156
M10	B-D	37.10	38.27 $\pm$ 0.06	38.43 $\pm$ 0.08	1.17	1.33	0.097

*Statistically significant difference ($P < .05$).

Values represent mean $\pm$ standard deviation.

Deviation values were calculated as the absolute difference relative to the master reference model.

DISCUSSION

The null hypothesis was partially rejected, as dimensional accuracy was influenced by both fabrication workflow and measurement span. Gypsum casts demonstrated smaller deviations in localized measurements, whereas additively manufactured models showed comparable behavior across several inter-point distances. These findings suggest that dimensional discrepancies are not uniformly distributed throughout the model and may depend on the evaluated span, which is consistent with previous studies reporting variation in distortion patterns across different arch regions (8,14-18).

Gypsum casts continue to serve as the reference standard because of their predictable reproduction of surface detail and dimensional stability. (1,3) However, conventional workflows remain susceptible to distortion introduced during impression making, stone expansion, material handling, and storage. These cumulative factors may contribute to dimensional variability, particularly when multiple procedural steps are involved.

Additively manufactured models reduce several sources of error associated with analog workflows by eliminating impression removal and gypsum pouring procedures. Previous studies have shown that digital workflows combining

intraoral scanning and additive manufacturing can achieve clinically acceptable dimensional accuracy (2,4,19). In the present study, the comparable deviations observed in several transverse and diagonal measurements suggest that additively manufactured models can reproduce broader spatial relationships with acceptable consistency.

Dimensional behavior in printed models is influenced by multiple manufacturing variables (11,12). Printing technology, layer thickness, build orientation, resin properties, and postprocessing protocols have all been associated with dimensional outcomes (10,13). The use of standardized printing parameters in the present study may explain the relatively consistent deviations observed among printed specimens.

The greater discrepancies identified in localized measurements may reflect cumulative error introduced during digital acquisition and polymerization processes. Small deviations generated during scanning, STL conversion, printing, or postcuring may become more evident over short measurement spans, whereas extended distances may distribute these discrepancies more evenly.

From a clinical perspective, for diagnostic casts, orthodontic appliances, and treatment planning workflows, the observed deviations are unlikely to compromise clinical applicability. Gypsum casts demonstrated greater precision in short-span measurements, while additively manufactured models provided dimensional agreement across several inter-point distances. In addition to dimensional performance, digital workflows offer practical advantages related to reproducibility, digital storage, and integration with CAD-CAM systems (4-6).

This study has limitations. The *in vitro* design does not reproduce clinical conditions,

and only one scanner, printing system, and resin material were evaluated. In addition, dimensional analysis was based on predefined linear measurements rather than three-dimensional superimposition techniques. Although linear measurements permit assessment of span-dependent distortion, three-dimensional deviation mapping may provide a more comprehensive evaluation of trueness and precision (21). Future investigations should compare different printing technologies, materials, and postprocessing strategies while incorporating three-dimensional analysis methods.

CONCLUSION

Dimensional accuracy was influenced by fabrication workflow and measurement span. Gypsum casts demonstrated greater precision in localized measurements, whereas additively manufactured models showed comparable performance across broader distances. Both workflows produced clinically acceptable deviations, supporting the use of additively manufactured models as a reliable alternative for prosthodontic applications.

CONFLICTS OF INTEREST: The authors declare no conflict of interest.

FUNDING STATEMENT: This research did not receive any specific grant from public, commercial, or not-for-profit funding agencies.

AUTHOR CONTRIBUTION STATEMENT: Conceptualization and Design, L.W.H.D. and H.F.C.; Methodology and Validation, L.W.H.D. and H.F.C.; Investigation and Data Collection, J.Y.H. and L.T.C.; Formal Analysis, Data Interpretation, and Visualization, C.M.S.; Writing – Original Draft Preparation, C.M.S. and C.A.P.A.; Writing – Review and Editing, C.A.P.A.; Supervision, H.F.C.; Project Administration, L.W.H.D. All authors have read and agreed to the published version of the manuscript.

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