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To Compare and Evaluate the Effect of Various Printing Orientations on Surface Characteristics, Trueness, And Fit of Additively Manufactured Dies

Dr. Prithu Singh, Dr. Garima Agarwal, Dr. Praveen Rai

[1.] *Postgraduate Student, Department of Prosthodontics, Crown & Bridge, Babu Banarasi Das College of Dental Sciences, Lucknow, India.*

[2.] *Professor, Department of Prosthodontics, Crown & Bridge, Babu Banarasi Das College of Dental Sciences, Lucknow, India.*

[3.] *Reader, Department of Prosthodontics, Crown & Bridge, Babu Banarasi Das College of Dental Sciences, Lucknow, India.*

Corresponding Author: *Dr. Prithu Singh*
Department of Prosthodontics, Crown & Bridge,
Babu Banarasi Das College of Dental Sciences, Lucknow, India.

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Abstract

Statement of Problem: Ongoing research evaluates the accuracy and surface characteristics of additively manufactured dies for dental applications to ensure clinical reliability.

Purpose: This in vitro study investigates how printing orientation affects surface characteristics, trueness, and fit of 3D-printed dies to guide optimal orientation selection for clinical and laboratory use.

Materials and Methods: Sixty-one samples were divided into one control group and three subgroups (15 samples each). A mandibular first molar was prepared with a 1mm shoulder finish line and occlusal indentations. The control group used polyvinylsiloxane impressions and Type IV gypsum casts. STL files from a digitized mandibular cast were used to design and additively manufacture 15 dies at 30°, 60°, and 90° build angles. Trueness and proximal fit were assessed via linear measurements (buccolingual, mesiodistal, mesio-proximal, disto-proximal) using a digital vernier caliper, with two operators minimizing bias. Surface roughness was evaluated with a surface roughness tester.

Results: Intragroup comparison of 3D-printed dies showed consistent accuracy in simpler regions (disto-proximal, $p = 0.062$) across build angles, but significant variability in complex regions (mesio-proximal, $p < 0.001$), with 90° offering the highest precision. Surface roughness was significantly lower in 3D-printed dies compared to conventional dies ($p = 0.001$).

Conclusion: 3D-printed dies demonstrate superior surface smoothness and precision, particularly at a 90° build angle, which excels in complex anatomical regions. Simpler areas maintain consistent accuracy across all angles (30°, 60°, 90°), supporting the reliability of additive manufacturing for dental applications.

Clinical Relevance: The 90° orientation enhances marginal fit and surface quality, reducing chairside adjustments and improving restoration longevity. These findings advocate for the adoption of 3D-printed dies in dental practice, offering precision and efficiency over traditional methods.

Keywords: 30 degree 60-degree 90 degree additively manufactured dies surface roughness 3d printed

I. INTRODUCTION

Additive manufacturing (3D printing) has revolutionized dentistry by enabling precise fabrication of 3D-printed dies for dental prosthetics.[1,2] Printing orientation significantly influences surface roughness, trueness, and fit, critical for restoration functionality and longevity.[3] Unlike subtractive methods, 3D printing builds complex geometries layer by layer from digital designs, offering customization and efficiency. [4,5] Printing orientation affects layer alignment, surface texture, and dimensional accuracy, impacting die quality. [7,8,9,10] Surface roughness is pivotal; excessive roughness can cause marginal discrepancies, poor occlusion, and debris accumulation, complicating procedures like wax pattern fabrication.[15,16,17] Smoother surfaces enhance fit, marginal integrity, and restoration durability. Trueness, the accuracy of the die relative to the digital design, and fit, its ability to interface with components, are essential for clinical success.[18,19] Factors like layer thickness, material properties, and storage conditions affect these parameters.[13,20,21] Poor trueness or fit can lead to misfits, requiring adjustments and risking clinical failure.[19] Different printing orientations yield varying surface finishes, with some reducing the "stair-stepping" effect for smoother results, while others increase irregularities, affecting fit and necessitating extensive post-processing.[25] This post-processing may alter critical dimensions, compromising accuracy. Optimizing printing orientation is key to achieving superior surface quality, trueness, and fit, enhancing clinical outcomes in dental applications.[5,22,23] This study compares the effects of various printing orientations on 3D-printed dies, aiming to elucidate their impact on surface characteristics and fit. By providing insights into optimal orientation selection, it seeks to guide dental professionals in improving the precision, efficiency, and performance of additively manufactured dies for dental restorations.[11,12,26,27]

II. MATERIALS AND METHODOLOGY

The objective was to evaluate and compare conventional stone dies with 3D printed dies fabricated at 30°, 60°, and 90° orientations for single, natural tooth-supported crowns. Efforts were made to standard procedures throughout to minimize variability and ensure the reliability of observations and results.

Sample Size and Distribution:

The mandibular right molar on the Nissin hard gingiva model served as the reference sample. In total, 61 samples were used, comprising:

1. One reference model
2. Fifteen control group samples
3. Fifteen Model A samples (30° printing orientation)
4. Fifteen Model B samples (60° printing orientation)
5. Fifteen Model C samples (90° printing orientation)

III. METHODOLOGY

Reference Model Preparation and Data Collection

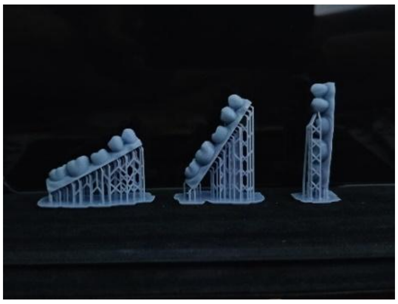
A typodont containing an acrylic resin tooth (Figure 1) was used, and the mandibular first molar was prepared according to biomechanical principles—featuring a 1 mm shoulder finish line, 6° axial convergence, and 1.5 to 2 mm occlusal reduction to accommodate a zirconia restoration. Indentations were created using a round diamond point bur (MANI INC, BR-46) at specific points for measurement. All linear distances between indentations were measured using a digital vernier caliper to establish a reference dataset, with all data collected by a single examiner to maintain consistency.

Fabrication of Conventional Dies (Control Group)

Following preparation, a perforated impression tray was selected, coated with tray adhesive, and used to record an impression of the prepared tooth via the single-step putty wash technique using polyvinylsiloxane (PVS) impression material. Impressions were poured with Type IV gypsum to produce casts with a 15 mm base, over which a secondary base was poured.

Preparation of Additively Manufactured 3D Printed Dies

The mandibular cast with prepared right first molar was scanned using a desktop scanner, digitized, and exported as an STL file into design software. Dies were designed and imported into nesting software; fifteen dies for each orientation (30°, 60°, and 90°) were 3D printed at a layer thickness of 50 µm.



Evaluation of Trueness and Proximal Fit

The previously created indentations served as reference points for measuring linear dimensions in buccolingual, mesiodistal, mesio-proximal, and disto-proximal directions. A digital vernier caliper was used to measure the distance from the inner edge of one indentation to its counterpart. Measurements were performed on both conventional and 3D printed dies (at all printing orientations) by two operators to reduce bias.

Evaluation of Surface Roughness

- Surface roughness was assessed on unfinished specimen surfaces using a contact profilometer—a precision instrument that measures surface texture via a stylus tracing the surface. This method yields detailed quantitative data regarding surface topography, relevant in manufacturing and quality control.

IV. Result

The document compares the precision and trueness of conventional, 3D printed, and master cast dental dies across different anatomical regions and build orientations. Key findings include:

- **Dimensional Accuracy:** The disto-proximal region showed no significant differences among the methods, while the disto-mesio region revealed significant deviations, with conventional dies showing higher mean deviations.
- **Precision:** The bucco-lingual region had the highest precision for 3D printed dies at 90°, indicating superior accuracy in this area.
- **Build Orientation:** 3D printed dies showed variable precision depending on the build angle, with 90° generally producing the highest accuracy.
- **Surface Roughness:** 3D printed dies had smoother surfaces at 30° and 90° compared to conventional dies.
- **Statistical Analysis:** Significant differences were confirmed in many pairwise comparisons, particularly between conventional and 3D printed dies.

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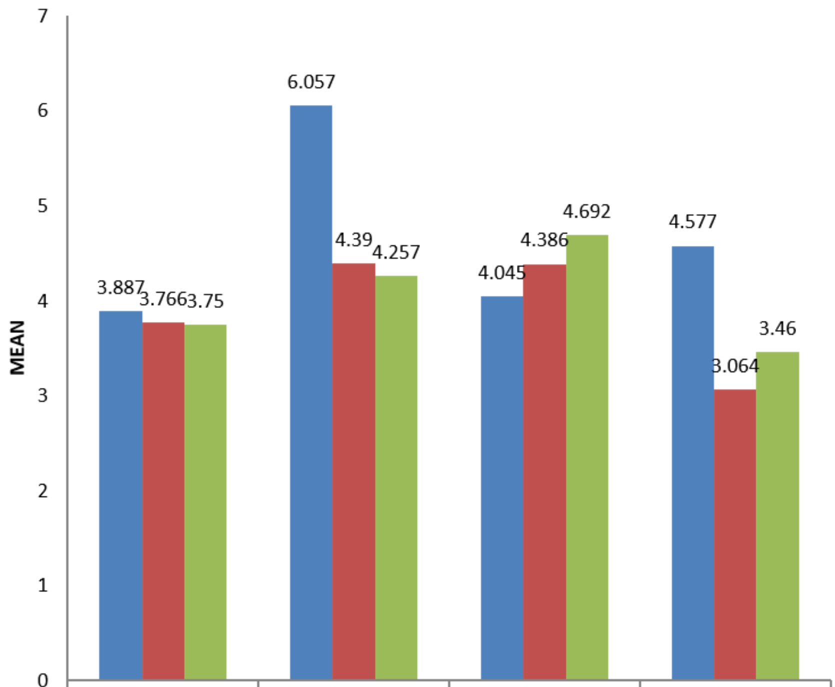
INTERGROUP COMPARISON OF MEAN VALUES OF PRECISION AND TRUENESS OF PRINTED 3D (ADDITIVELY MANUFACTURED) 3D PRINTED DIES AND CONVENTIONAL STANDARD DIE VALUES AT 90 DEGREES



	Group A	Group B	Group C	Group D
Conventional Standard Values	3.887	6.057	4.045	4.577
Printed 3D Values	3.766	4.39	4.386	3.064
Master Cast Values	3.75	4.257	4.692	3.46

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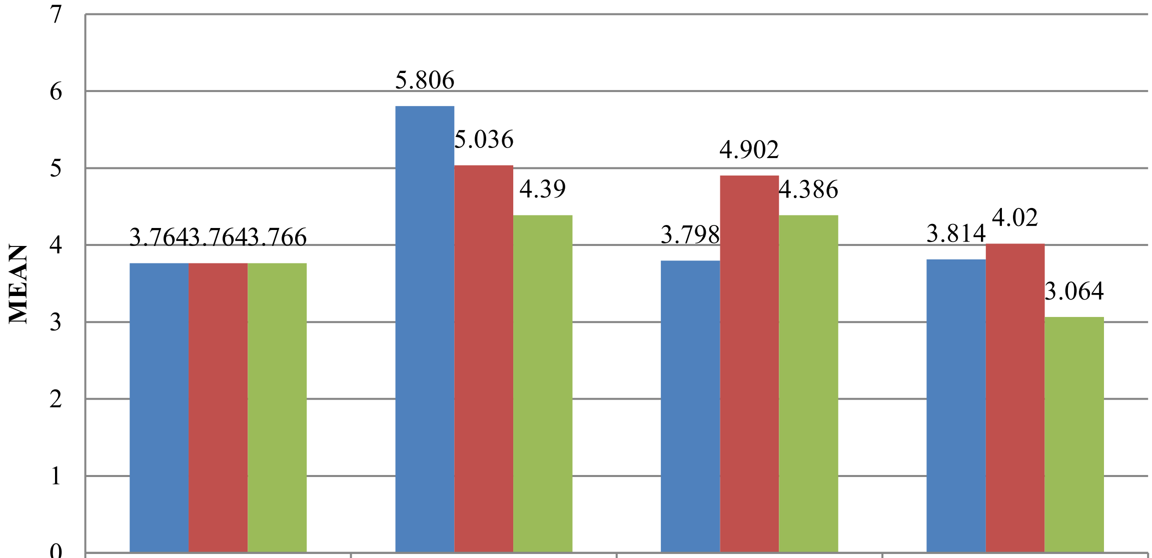
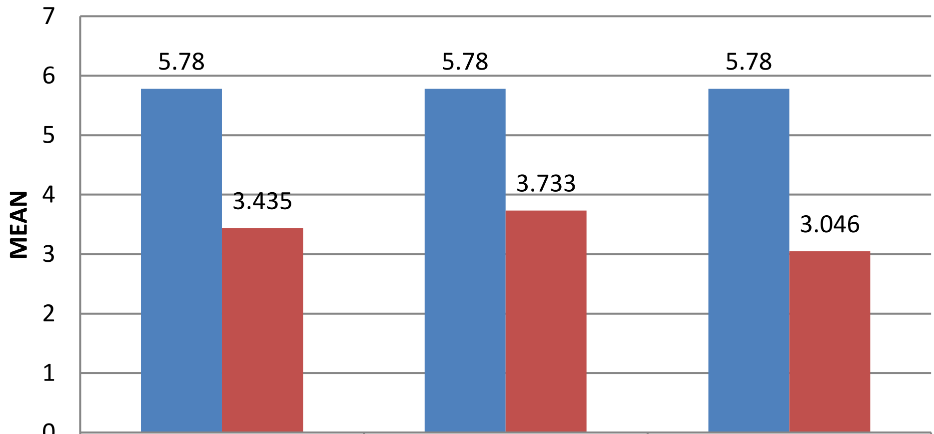
INTRAGROUP COMPARISON OF PRECISION AND TRUENESS FOR 3D PRINTED DIES AT 30°, 60°, AND 90°



	Group A (Disto-Proximal)	Group B (Disto-Mesio)	Group C (Mesio-Proximal)	Group D (Bucco-Lingual)
30°	3.764	5.806	3.798	3.814
60°	3.764	5.036	4.902	4.02
90°	3.766	4.39	4.386	3.064

INTERGROUP COMPARISON OF MEAN VALUES OF SURFACE ROUGHNESS BETWEEN CONVENTIONAL AND CONVENTIONAL STANDARD DIE VALUES AT ARIOUS DEGREES



	30 Degree	60 Degree	90 Degree
Conventional Standard Values	5.78	5.78	5.78
Printed 3D Values	3.435	3.733	3.046

V. Discussion

In Group A (Disto-Proximal), no statistically significant differences were observed among the conventional die (3.887 ± 0.334 mm), 3D-printed die (3.766 ± 0.085 mm), and master cast (3.750 ± 0.258 mm) ($p > 0.05$), demonstrating equivalent dimensional accuracy across fabrication techniques in this region. This uniformity is consistent with the observations of Cho SH et al.[35], who demonstrated that stereolithography (SLA)-based 3D-printed casts attain clinically acceptable accuracy in geometrically simpler areas, such as the disto-proximal region. The absence of significant inter-method differences implies that the disto-proximal area's uncomplicated anatomy mitigates errors inherent to 3D printing (e.g., layer adhesion failures or support structure artifacts) and conventional techniques (e.g., material distortion during impression-taking). The 90-degree orientation likely promotes superior layer alignment and support placement, thereby bolstering 3D-printed die accuracy in this zone, as corroborated by Hassanpour et al.[39]. Consequently, 3D-printed dies emerge as a viable substitute for conventional dies in disto-proximal restorations, potentially conferring benefits in workflow efficiency and cost-effectiveness.

Group B (Disto-Mesial) exhibited significant differences between the conventional die (6.057 ± 0.321 mm) and both the 3D-printed die (4.390 ± 0.300 mm) and master cast (4.257 ± 0.332 mm) ($p < 0.001$), with no significant disparity between the 3D-printed and master cast groups ($p > 0.05$). The elevated mean of the conventional die points to dimensional overestimation in traditional gypsum casting, attributable to material expansion or impression inaccuracies, as detailed by Cho SH et al.[35]. The close alignment between 3D-printed and master cast measurements affirms that additive manufacturing can match reference standards in the disto-mesial region, notwithstanding its curved contours and proximal contacts. This outcome diverges from the 60-degree orientation data, where all Group B pairwise comparisons were significant, indicating that the 90-degree orientation attenuates errors from scanning artifacts or material contraction, in line with Lin L et al 36. Enhanced 3D-printed die performance at 90 degrees may stem from improved geometric congruence between printing layers and the model's anatomy, thereby curtailing distortions in this anatomically demanding area.

In Group C (Mesio-Proximal), all pairwise comparisons were statistically significant, with the 3D-printed die (4.386 ± 0.098 mm) and master cast (4.692 ± 0.123 mm) yielding higher means than the conventional die (4.045 ± 0.256 mm) ($p < 0.01$ and $p < 0.001$, respectively), alongside a significant difference between 3D-printed and master cast groups ($p < 0.05$). The superior means of 3D-printed dies relative to conventional counterparts suggest a propensity for additive manufacturing to overestimate dimensions here, possibly due to printer resolution constraints or non-optimized printing parameters, as emphasized by Rungrojwittayakul et al [37]. Their investigation revealed that Digital Light Processing (DLP) or material jetting technologies can produce oversizing in regions with elaborate interproximal details, mirroring the mesio-proximal area's complexity. The notable separation between 3D-printed and master cast values, although closer than with conventional methods, underscores lingering inaccuracies potentially linked to resin polymerization dynamics or support remnants. The conventional die's diminished mean may arise from material warping or procedural inconsistencies in traditional impressions, highlighting trueness challenges in this region.

Group D (Bucco-Lingual) displayed statistical significance across all pairwise comparisons ($p < 0.001$ or $p < 0.01$), with the conventional die recording the highest mean (4.577 ± 0.459 mm), succeeded by the master cast (3.460 ± 0.254 mm) and 3D-printed die (3.064 ± 0.038 mm). The markedly reduced 3D-printed die mean implies dimensional underestimation, likely resulting from resin shrinkage post-polymerization or complications in support removal, as documented by George et al.[38]. Their work indicated that SLA-induced mechanical stresses precipitate inaccuracies in expansive surfaces akin to the bucco-lingual region. The conventional die's inflated mean could reflect expansion artifacts or impression errors, echoing Cho SH et al.[35]. Pronounced inter-method differences in this group illuminate the difficulties in securing accuracy amid variable thicknesses and surface intricacies, with the 90-degree orientation potentially amplifying support-related distortions in 3D printing.

The comparison of surface roughness between traditional stone dies and 3D-printed dies at 30°, 60°, and 90° orientations revealed a statistically significant reduction in roughness for 3D-printed dies across all tested angles, with $p = 0.001$ for each orientation. Conventional stone dies exhibited a mean surface roughness of 5.780 ± 0.412 µm, whereas 3D-printed dies demonstrated markedly lower values: 3.435 ± 0.308 µm at 30°, 3.733 ± 0.356 µm at 60°, and 3.046 ± 0.289 µm at 90°. These findings indicate a consistent and clinically meaningful improvement in surface quality with additive manufacturing, challenging the long-held assumption of superior finish in traditional gypsum dies.

The lowest roughness was observed at the 90° orientation (3.046 µm), representing a 47.3%

reduction compared to conventional dies. This result aligns closely with the observations of Unkovskiy et al.[9], who reported that vertical build orientations minimize stair-stepping artifacts and layer visibility, thereby optimizing surface smoothness in stereolithography (SLA)-printed dental models. The progressive improvement from 30° to 90° supports the findings of Kim et al [46,] who demonstrated that print orientation significantly influences surface topography, with perpendicular layer alignment reducing cumulative irregularities.

These outcomes are further corroborated by Christine et al [47], who compared 3D-printed models with conventional dental plaster and found significantly smoother surfaces in the printed group ($p < 0.01$), attributing this to controlled resin polymerization and absence of manual finishing variability inherent in stone die production. The consistency of statistical significance ($p = 0.001$) across all orientations in the present study reinforces the robustness of these findings and echoes Alharbi et al.[48], who concluded that optimized printing parameters—particularly build angle and layer thickness—can yield surface qualities superior to conventional methods.

VI. Conclusion

This study demonstrated that build orientation significantly affects the dimensional accuracy and surface quality of 3D-printed dental dies. Among the tested angles, the 90° orientation consistently provided superior accuracy—particularly in regions like disto-mesial, mesio-proximal, and bucco-lingual—and smoother surface finishes compared to 30° and 60° angles. areas like disto-proximal, all methods showed comparable accuracy, indicating less sensitivity to orientation. The findings suggest that with optimal orientation, 3D printing can match or surpass conventional methods, offering a reliable, efficient alternative for dental die fabrication. However, further studies with diverse technologies and clinical conditions are needed to confirm these results.

Clinical implication: 3D-printed dies can reliably replace conventional dies for simpler dental regions, and a vertical (90°) build orientation is recommended for improving precision and trueness in complex areas.

In summary, surface quality and dimensional accuracy of 3D-printed dental dies are dependent on build orientation and anatomical region, with notable advantages over traditional stone dies, especially when optimal print parameters are selected.

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