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Effect of 3D printing technology and print orientation on the trueness of additively manufactured definitive casts with different tooth preparations

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ABSTRACT

Objectives: To evaluate the fabrication trueness of additively manufactured maxillary definitive casts with various tooth preparations fabricated with different 3-dimensional (3D) printers and print orientations.
Methods: A maxillary typodont with tooth preparations for a posterior 3-unit fixed partial denture, lateral incisor crown, central incisor and canine veneers, first premolar and second molar inlays, and a first molar crown was digitized with an industrial scanner. This scan file was used to fabricate definitive casts with a digital light processing (DLP) or stereolithography (SLA) 3D printer in different orientations (0-degree, 30-degree, 45-degree, and 90-degree) ($n = 7$). All casts were digitized with the same scanner, and the deviations within each preparation site were evaluated. Generalized linear model analysis was used for statistical analysis ($\alpha = 0.05$).
Results: The interaction between the 3D printer and the print orientation affected measured deviations within all preparations ($P \leq 0.001$) except for the lateral incisor crown and canine veneer ($P \geq 0.094$), which were affected only by the main factors ($P < 0.001$). DLP-90 mostly led to the highest and DLP-0 mostly resulted in the lowest deviations within posterior tooth preparations ($P \leq 0.014$). DLP-30 led to the lowest deviations within the first premolar inlay and DLP-45 led to the lowest deviations within the central incisor veneer preparation ($P \leq 0.045$).
Conclusions: Posterior preparations of tested casts had the highest trueness with DLP-0 or DLP-30, while central incisor veneer preparations had the highest trueness with DLP-45. DLP-90 led to the lowest trueness for most of the tooth preparations.
Clinical Significance:: Definitive casts with tooth preparations fabricated with the tested DLP 3D printer and the print orientation adjusted on tooth preparation may enable well-fitting restorations. However, 90-degree print orientation should be avoided with this 3D printer, as it led to the lowest fabrication trueness.

1. Introduction

Stone casts fabricated by using conventional impressions have been the standard tool to diagnose the intraoral situation and fabricate restorations [1]. However, direct digital workflow has eliminated the need for technique-sensitive conventional impressions [2,3] and physical casts that require storage and are prone to deformation [4–8]. Nevertheless, for those cases that require a physical cast, additive or subtractive manufacturing can be used to fabricate them. In this respect, additive manufacturing is a more sustainable method [2,3,9] as complex structures can be fabricated with minimum material waste [10]. Vat polymerization is an additive manufacturing method based on the layer-by-layer polymerization of a photosensitive resin in a vat with a light source, and commonly used to fabricate dental casts [11,12]. Three-dimensional (3D) printers that use digital light processing (DLP) or stereolithography (SLA) technologies are based on vat polymerization [2,13,14], and mainly differ from each other with the light source used to polymerize the resin [7,9,15,16]. DLP-based 3D printers use a digital light projector and polymerize an entire layer at once, whereas SLA-based 3D printers use a laser and polymerize a spot at once until the entire layer is polymerized [2,9].

Fabrication trueness of a definitive cast is critical to replicate the intraoral situation [17], and different parameters were reported to affect this outcome [18]. Among these factors, print orientation, which is the

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position of the printed object with respect to the build platform [19,20], is an adjustable parameter [8]. Print orientation not only affects the inherent properties of the printed object but as the geometry is changed spatially, the printing duration and consumed resin also vary due to different number of layers, even if the same object is printed.

Even though the effect of 3D printers [6,7,9,14–16,21–24] or print orientations [8,18,19,25] on the fabrication trueness of dentate casts was investigated in previous studies, the combined effect of these factors on the fabrication trueness of definitive dentate casts has not been evaluated. In addition, only one study has focused on the effect of 3D printers on fabrication trueness when different tooth preparations were considered [2]. However, that study was performed on removable dies rather than definitive casts [2]. A study based on how 3D printers and print orientation affect the fabrication trueness of definitive casts with different tooth preparations could expand the knowledge of clinicians and dental technicians and potentially facilitate the daily cast fabrication workflow. Therefore, the present study aimed to evaluate how different 3D printers and print orientations affect the fabrication trueness of additively manufactured definitive casts when different tooth preparations were considered. The null hypothesis was that the 3D printer and print orientation would not affect the fabrication trueness of definitive casts within tested tooth preparations.

2. Material and methods

A priori power analysis (α=0.05, 1-β=95 %, $f = 0.68$) with the results of a previous study on the effect of print orientation on the fabrication trueness of maxillary casts was performed, and 7 specimens per group were deemed sufficient [18]. A master maxillary typodont (Dentsply Sirona, Bensheim, Germany) with tooth preparations for different restoration designs (Fig. 1) was digitized by using an industrial scanner (Artec Micro; Artec 3D, Luxembourg City, Luxembourg) with 10 µm accuracy [26] and the manufacturer's proprietary software program (Artec Studio v17; Artec 3D, Luxembourg City, Luxembourg) to generate a reference standard tessellation language (STL) file (R-STL). This R-STL was used to fabricate definitive casts by using either a DLP-based (MAX UV; Asiga, Sydney, Australia) or an SLA-based (Form 3B+; Formlabs, Somerville, MA, USA) 3D printer.

To fabricate the specimens, the R-STL was imported into nesting software programs of the DLP (Composer v1.3; Asiga, Sydney, Australia) and SLA (PreForm; Formlabs, Somerville, MA, USA) 3D printers, and positioned on the build platform in 4 different print orientations (0-degree, DLP-0 and SLA-0; 30-degree, DLP-30 and SLA-30; 45-degree, DLP-45 and SLA-45; 90-degree, DLP-90 and SLA-90; Fig. 2) (n = 7). The proprietary dental model resin of each manufacturer (DentaMODEL; Asiga, Sydney, Australia for DLP 3D printer and Model Resin V3; Formlabs, Somerville, MA, USA for SLA 3D printer) was used to fabricate specimens with a layer thickness of 100 µm [4,9] after automatically generating nesting software program specific supports with different designs and numbers for each orientation. Each cast was fabricated in a separate print job and the parameters of a single printing job automatically calculated by the nesting software programs for each group are given in Table 1. After fabrication, DLP-fabricated casts were ultrasonically (Wash & Cure 2.0; Anycubic, Shenzhen, China) cleaned in isopropyl alcohol for 10 min (5 min of prewash and 5 min of postwash) and postpolymerized by using a xenon polymerization device (OtoFlash G171; NK Optik GmHb, Baierbrunn, Germany) under nitrogen oxide gas atmosphere for 4000 flashes (2000 × 2), while SLA-fabricated casts were ultrasonically (Form Wash; Formlabs, Somerville, MA, USA) cleaned in isopropyl alcohol for 10 min and postpolymerized in a light emitting diode polymerization device (Form Cure; Formlabs, Somerville, MA, USA) for 30 min at 60 °C.

All casts were digitized within 48 h after fabrication by using the same industrial scanner to generate cast STLs (C-STLs), and they were stored in light-proof boxes at room temperature until being scanned [17]. The R-STL and C-STLs were imported into a metrology-grade 3D analysis software program (Geomagic Control X v.2022.1.1; 3D Systems) to evaluate the deviations of the C-STLs from the R-STL. The R-STL was imported as the reference file and automatically segmented by using the "auto segment" feature of the "region tool" of the software program. Automatically segmented regions were then merged by using the "merge" feature of the "region tool" to define each preparation and nonprepared surface individually. The quick initial alignment and iterative closest point-based best-fit alignment tools of the software program, which are automated processes that do not require operator-based decisions, were used to superimpose C-STLs over the R-STL (Fig. 3). After superimpositions, the "3D Compare" tool of the software program was used to generate color maps with red representing overcontoured surfaces, blue representing undercontoured surfaces, and green representing acceptable deviations (Figs. 4 and 5). The deviations of C-STLs from the R-STL at each defined tooth preparation region were automatically calculated by using the root mean square method. One experienced dentist (M.D.) operated the optical scanner and performed the analyses throughout the process.

The Shapiro-Wilk test was used to evaluate the normality of data,

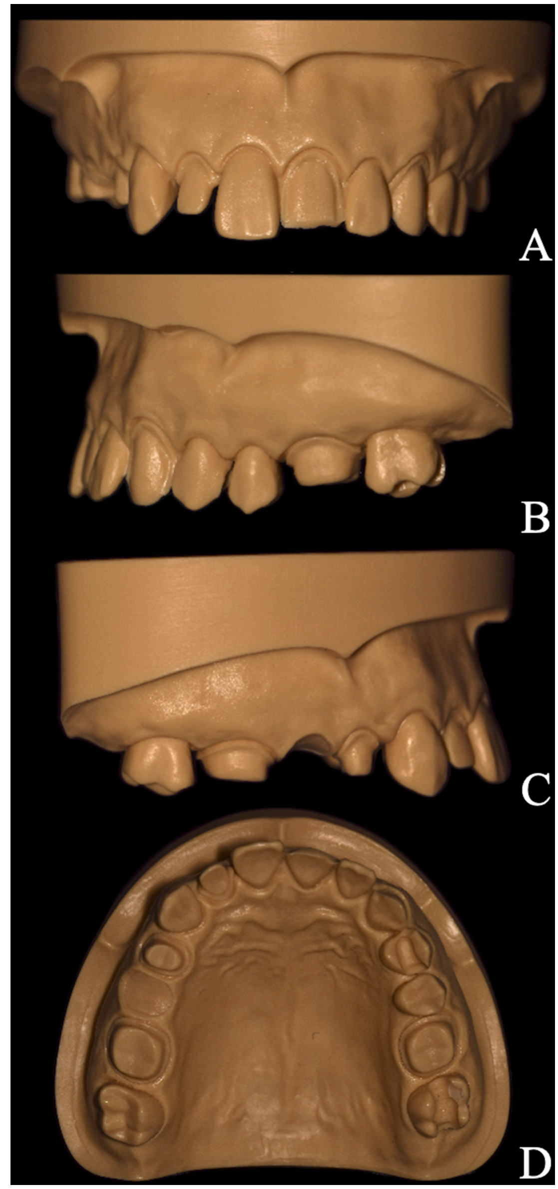

Fig. 1. Master maxillary typodont from various aspects. A, Labial aspect; B, Left buccal aspect; C, Right buccal aspect; D, Occlusal aspect.

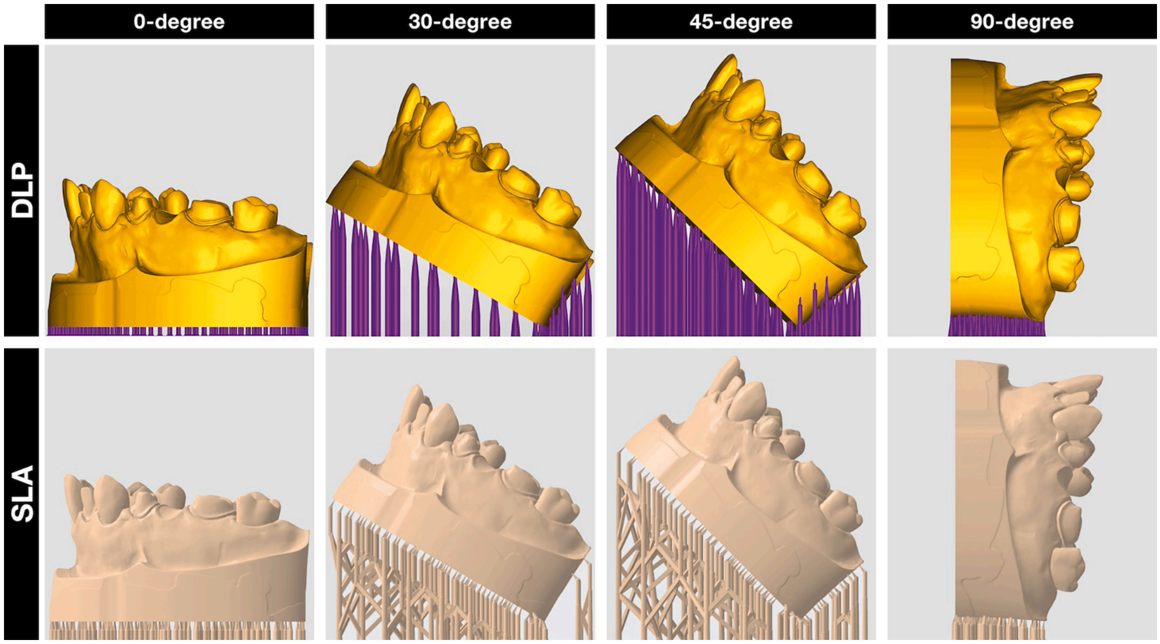

Fig. 2. Print orientations within each 3D printer with supports of different designs and numbers.

Table 1
Parameters of single printing job within each 3D printer-print orientation pair.

	Print Duration		Number of Layers		Consumed Resin Volume	
	DLP	SLA	DLP	SLA	DLP	SLA
0-degree	1 h 13 m	1 h 48 m	359	401	62.48 ml	73.03 ml
30-degree	1 h 59 m	2 h 27 m	588	630	64.60 ml	70.08ml
45-degree	2 h 11 m	2 h 37 m	649	691	67.13 ml	69.89 ml
90-degree	2 h 6 m	2 h 20 m	621	650	62.11 ml	68.45 ml

which validated the normal distribution of measured deviations within each tooth preparation. Therefore, generalized linear model analyses, which included the main factors of 3D printer and print orientation, and the interaction between them, were performed to evaluate the measured deviations within each tooth preparation. All analyses were performed by using a statistical analysis software program (SPSS v25; IBM Corp) at a significance level of $\alpha = 0.05$.

3. Results

Table 2 shows the results of the generalized linear model analysis within each tooth preparation. The interaction between the 3D printer and the print orientation affected the measured deviations within each region ($P \leq 0.001$) except for the lateral incisor crown ($P = 0.278$) and canine veneer ($P = 0.094$) regions. The 3D printer affected the measured deviations in the posterior fixed partial denture, lateral incisor crown, canine veneer, and first premolar inlay regions ($P \leq 0.001$), while the print orientation affected measured deviations in every region ($P < 0.001$).

For the posterior fixed partial denture, DLP-90 led to the highest deviations, followed by SLA-90 ($P < 0.001$). DLP-0 resulted in the lowest deviations ($P \leq 0.014$), followed by DLP-30 ($P \leq 0.002$). The DLP 3D printer led to lower deviations than the SLA 3D printer ($P < 0.001$). Among tested orientations, 90-degree led to the highest ($P < 0.001$) and 0- and 30-degree led to the lowest deviations ($P \leq 0.005$) (Table 3). For the lateral incisor crown, the DLP 3D printer led to lower deviations ($P < 0.001$), and 90-degree print orientation led to the highest deviations ($P < 0.001$) (Table 4).

For the central incisor veneer, DLP-90 resulted in the highest and DLP-45 in the lowest deviations ($P \leq 0.020$). In addition, DLP-30 led to higher deviations than DLP-0 and SLA-90 ($P \leq 0.049$). The casts with 45-degree print orientation had the lowest deviations, while the casts with 90-degree orientation had higher deviations than those with 0-degree ($P \leq 0.018$) (Table 5). For the canine veneer, the DLP 3D printer led to lower deviations ($P < 0.001$). The casts with 0-degree print orientation had the highest and those with 30- and 45-degree print orientation had the lowest deviations ($P \leq 0.018$) (Table 6).

For the first premolar inlay, DLP-90 and SLA-90 led to the highest deviations ($P \leq 0.003$), followed by SLA-45 and SLA-0 ($P \leq 0.019$). DLP-30 resulted in lower deviations than the remaining pairs ($P \leq 0.045$) except for DLP-45 ($P = 0.499$). SLA-30 led to higher deviations than DLP-45 and DLP-0 ($P \leq 0.003$). The DLP 3D printer led to lower deviations ($P < 0.001$). The casts with 90-degree print orientation had the highest and those with 30-degree print orientation had the lowest deviations ($P \leq 0.020$) (Table 7).

For the first molar crown, DLP-0 resulted in the lowest and DLP-90 resulted in the highest deviations ($P < 0.001$). SLA-90 led to higher deviations than DLP-30 and SLA-45 ($P \leq 0.037$), and DLP-45 led to higher deviations than SLA-45 ($P = 0.033$). The casts with 0-degree print orientation had the lowest and those with 90-degree orientation had the highest deviations ($P < 0.001$) (Table 8).

For the second molar inlay, DLP-0 casts had the lowest and DLP-90 casts had the highest deviations ($P < 0.001$). SLA-30, DLP-45, and SLA-0 casts had similar deviations ($P \geq 0.172$) that were only higher than those of DLP-0. The deviations of the remaining pairs were SLA-45, DLP-30, and SLA-90 in increasing order ($P \leq 0.038$). The casts with 0-degree print orientation had the lowest and those with 90-degree orientation had the highest deviations ($P < 0.001$) (Table 9).

For the nonprepared tooth surfaces, DLP-0 casts had the lowest deviations followed by SLA-0, and DLP-90 casts had the highest deviations followed by SLA-90 ($P \leq 0.010$). SLA-45 casts had higher deviations than DLP-30 ($P = 0.036$). The casts with 0-degree print orientation had the lowest and those with 90-degree orientation had the highest deviations ($P < 0.001$) (Table 10).

4. Discussion

The null hypothesis of the present study was rejected as tested 3D printers and print orientations affected the fabrication trueness of

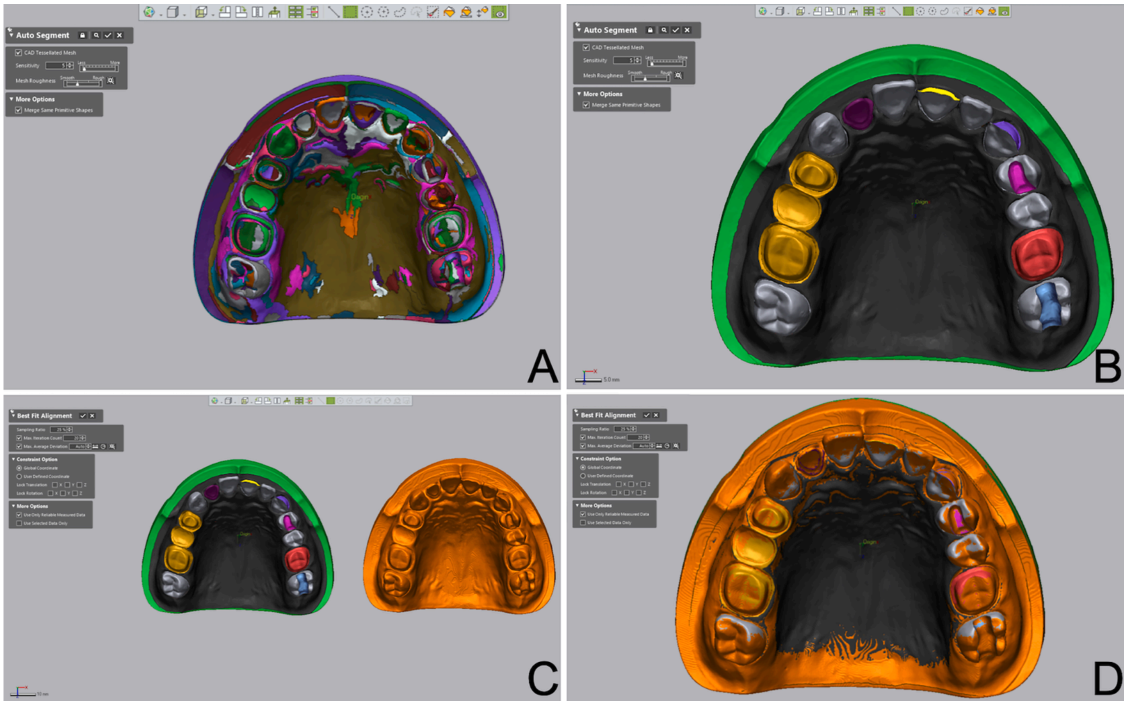

Fig. 3. Superimposition process of C-STL over R-STL. A; R-STL after automatic segmentation. B; Individually merged preparation areas and nonprepared tooth surfaces. C; R-STL with merged surfaces and C-STL before superimposition. D; C-STL superimposed over R-STL. C-STL, Cast standard tessellation language file; R-STL, Reference standard tessellation language file.

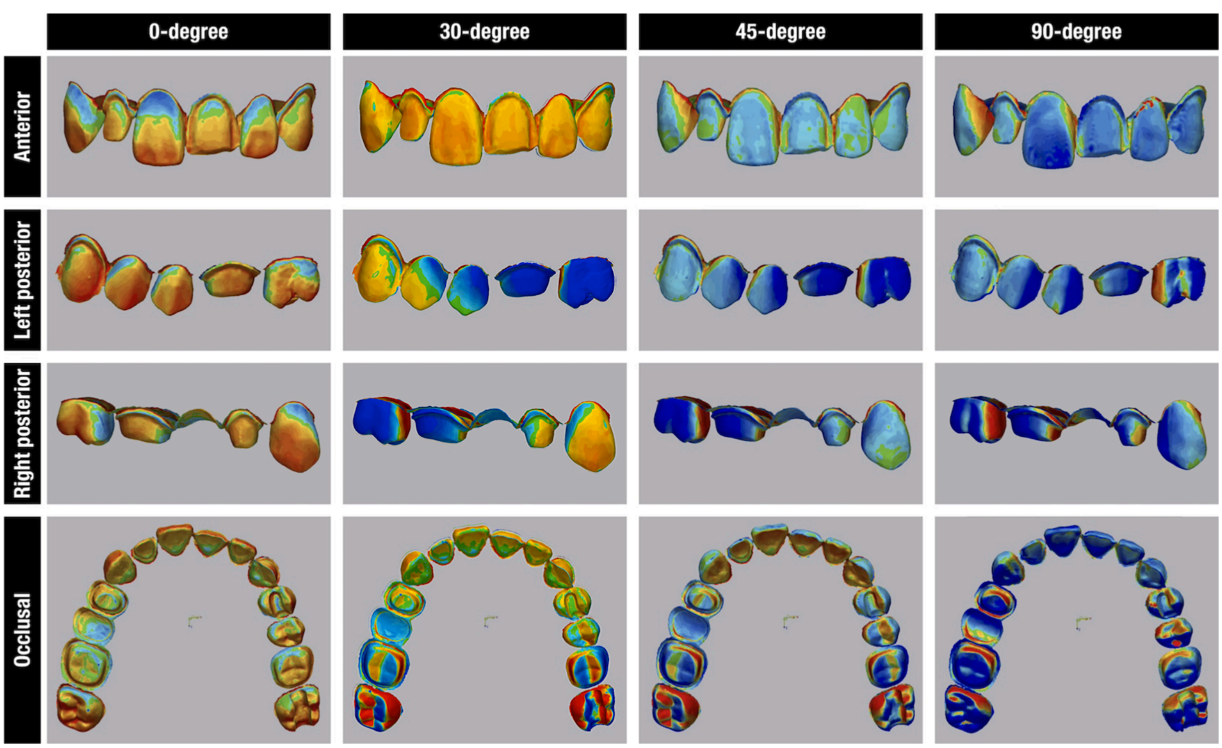

Fig. 4. Representative color maps of casts with different print orientations within DLP 3D printer.

maxillary definitive casts, regardless of the evaluated region. Casts fabricated with the DLP 3D printer in 0-degree print orientation had the highest trueness within the posterior fixed partial denture, left first molar crown, left second molar inlay regions, and nonprepared tooth surfaces, while those fabricated with 45-degree orientation had the highest trueness within central incisor laminate veneer and those fabricated with 30-degree orientation had the highest trueness within first premolar inlay region. In addition, DLP-90 casts mostly had the lowest trueness within evaluated regions. Even though the significant effect of the interaction between the main factors complicates attributing these results directly on tested 3D printers or print orientations, some interpretations based on the fundamentals of 3D printing still can

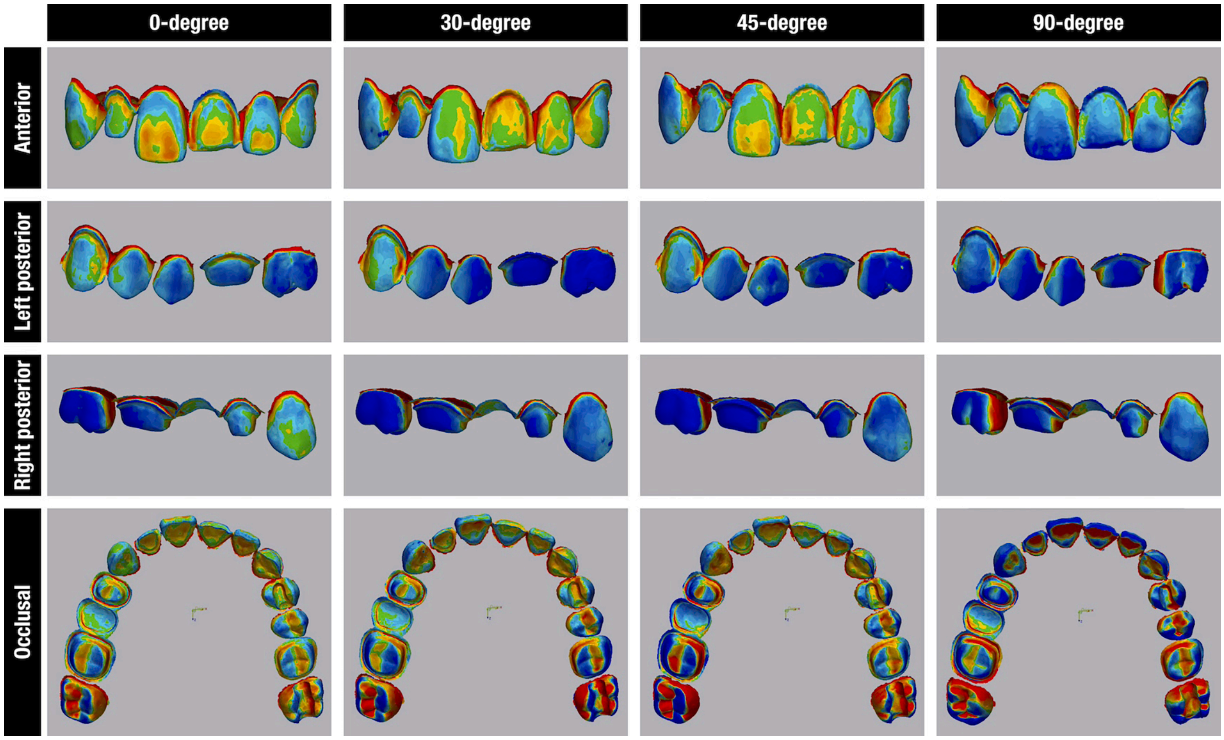

Fig. 5. Representative color maps of casts with different print orientations within SLA 3D printer.

Table 2
Results of generalized linear model analyses for each region.

	Posterior fixed partial denture	Lateral incisor crown	Central incisor veneer	Canine veneer	First premolar inlay	First molar crown	Second molar inlay	Nonprepared surfaces
3D printer	0.001	<0.001	0.633	<0.001	<0.001	0.903	0.086	0.576
Angle	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
3D printer × Angle	<0.001	0.278	<0.001	0.094	0.001	<0.001	<0.001	<0.001

Table 3
Mean ±standard deviation values of measured deviations (μm) for each 3D printer-print orientation pair within posterior fixed partial denture preparation.

	3D printer		
Print orientation	DLP	SLA	Total
0-degree	44.8 ± 3.9^{A}	76.7 ± 9.0^{C}	$60.7 \pm 17.9^{*}$
30-degree	56.5 ± 9.4^{B}	74.2 ± 10.7^{C}	$65.3 \pm 13.3^{*}$
45-degree	71.2 ± 14.6^{C}	78.4 ± 9.9^{C}	$74.8 \pm 12.6^{\#}$
90-degree	124.2 ± 11.1^{E}	102.7 ± 3.3^{D}	$113.5 \pm 13.7^{\wedge}$
Total	$74.2 \pm 32.5^{*}$	$83.0 \pm 14.3^{\#}$	

Different superscript uppercase letters indicate significant differences among 3D printer-print orientation pairs, while different superscript symbols indicate significant differences between 3D printers and among print orientations. Total values are derived from pooled data ($P < 0.05$).

Table 4
Mean ±standard deviation values of measured deviations (μm) for each 3D printer-print orientation pair within lateral incisor crown preparation.

	3D printer		
Print orientation	DLP	SLA	Total
0-degree	37.1 ± 5.5	52.9 ± 7.6	$45.0 \pm 10.4^{*}$
30-degree	40.1 ± 4.4	50.1 ± 7.3	$45.1 \pm 7.8^{*}$
45-degree	44.4 ± 10.8	50.0 ± 4.3	$47.0 \pm 8.4^{*}$
90-degree	62.8 ± 11.3	75.7 ± 3.2	$69.3 \pm 10.4^{\wedge}$
Total	$46.1 \pm 13.0^{*}$	$57.1 \pm 12.4^{\#}$	

Different superscript symbols indicate significant differences between 3D printers and among print orientations. Total values are derived from pooled data ($P < 0.05$).

be made. Tested DLP 3D printer mostly led to higher trueness, which can be related to the uniform and simultaneous polymerization within each layer [9]. The layers of an object represent its horizontal cross-section when it is positioned with 90-degree on the build platform and the staircase effect, which is the loss of geometry in vertical direction [20], becomes more prominent with this orientation. In addition, objects printed with this orientation may require more support to improve stability; however, in the present study, DLP-90 and SLA-90 casts had the lowest number of supports. The anterior teeth on a dental arch have prominent features that extend outwards and upwards from the base of a dental cast, which might result in overhangs that impair trueness during printing. This can also be attributed to the left first premolar for the master model tested in the present study as it is not positioned vertically to the base of the model. Changing the print orientation may have reduced overhangs for these regions along with improved overlapping of consecutive layers that reduce the staircase effect. The measured deviations of the lateral incisor crown and canine laminate veneer regions also support these interpretations as 30- and 45-degree print orientation improved trueness. Nevertheless, a recent systematic review on the fabrication accuracy of additively manufactured dental casts reported that deviations up to 200 μm can be acceptable for prosthetic applications [3]. In the present study, the mean deviation values exceeded 200 μm in only 2 situations within DLP-90 casts. Even though the mean

Table 5
Mean ±standard deviation values of measured deviations (μm) for each 3D printer-print orientation pair within central incisor laminate veneer preparation.

Print orientation	3D printer		Total
	DLP	SLA	
0-degree	34.6 ± 6.1^{B}	44.1 ± 6.8^{BC}	$39.4 \pm 7.9^{\#}$
30-degree	44.7 ± 15.1^{C}	42.0 ± 8.8^{BC}	$43.3 \pm 12.0^{\#\wedge}$
45-degree	22.3 ± 4.1^{A}	39.3 ± 5.2^{BC}	$30.8 \pm 9.9^{*}$
90-degree	63.4 ± 20.2^{D}	34.3 ± 3.8^{B}	$48.8 \pm 20.6^{\wedge}$

Different superscript uppercase letters indicate significant differences among 3D printer-print orientation pairs, while different superscript symbols indicate significant differences among print orientations. Total values are derived from pooled data ($P < 0.05$).

Table 6
Mean ±standard deviation values of measured deviations (μm) for each 3D printer-print orientation within canine laminate veneer preparation.

Print orientation	3D printer		Total
	DLP	SLA	
0-degree	46.9 ± 12.5	61.8 ± 6.7	$54.3 \pm 12.3^{\#}$
30-degree	29.8 ± 6.0	44.6 ± 15.8	$37.2 \pm 13.8^{*}$
45-degree	26.0 ± 13.1	44.5 ± 6.2	$35.3 \pm 13.8^{*}$
90-degree	45.3 ± 9.5	45.6 ± 4.6	$45.5 \pm 7.2^{\wedge}$
Total	$37.0 \pm 13.8^{*}$	$49.1 \pm 11.6^{\#}$	

Different superscript symbols indicate significant differences between 3D printer and among print orientations. Total values are derived from pooled data ($P < 0.05$).

Table 7
Mean ±standard deviation values of measured deviations (μm) for each 3D printer-print orientation within first premolar inlay preparation.

Print orientation	3D printer		Total
	DLP	SLA	
0-degree	50.2 ± 4.9^{B}	86.4 ± 3.4^{D}	$68.3 \pm 19.2^{\#}$
30-degree	36.5 ± 4.8^{A}	70.3 ± 15.9^{C}	$53.4 \pm 20.9^{*}$
45-degree	41.1 ± 11.9^{AB}	88.1 ± 16.8^{D}	$64.6 \pm 28.1^{\#}$
90-degree	108.4 ± 27.0^{E}	112.5 ± 8.3^{E}	$110.5 \pm 19.3^{\wedge}$
Total	$59.0 \pm 32.7^{*}$	$89.3 \pm 19.3^{\#}$	

Different superscript uppercase letters indicate significant differences among 3D printer-print orientation pairs, while different superscript symbols indicate significant differences between printing technologies and among print orientations. Total values are derived from pooled data ($P < 0.05$).

Table 8
Mean ±standard deviation values of measured deviations (μm) for each 3D printer-print orientation pair within first molar crown preparation.

Print orientation	3D printer		Total
	DLP	SLA	
0-degree	36.2 ± 8.6^{A}	96.4 ± 8.1^{BCD}	$66.3 \pm 32.2^{*}$
30-degree	91.1 ± 12.9^{BC}	93.2 ± 16.8^{BCD}	$92.2 \pm 14.5^{\#}$
45-degree	104.3 ± 17.6^{CD}	88.4 ± 18.3^{B}	$96.4 \pm 19.1^{\#}$
90-degree	151.1 ± 23.9^{E}	106.6 ± 3.2^{D}	$128.9 \pm 28.3^{\wedge}$

Different superscript uppercase letters indicate significant differences among 3D printer-print orientation pairs, while different superscript symbols indicate significant differences among print orientations. Total values are derived from pooled data ($P < 0.05$).

deviation of nonprepared tooth surfaces within DLP-90 casts was higher than this threshold, the difference was just 8 μm and may be clinically negligible. Therefore, it can be stated that only the mean deviation of the second inlay region within DLP-90 casts was higher than 200 μm, and most of the casts fabricated by using tested 3D printer-print orientation pairs can be considered suitable for prosthetic applications.

Table 9
Mean ±standard deviation values of measured deviations (μm) for each 3D printer-print orientation pair within second molar inlay preparation.

Print orientation	3D printer		Total
	DLP	SLA	
0-degree	57.3 ± 7.9^{A}	112.7 ± 21.0^{B}	$85.0 \pm 32.6^{*}$
30-degree	149.9 ± 20.7^{D}	101.7 ± 17.6^{B}	$125.8 \pm 31.1^{\#}$
45-degree	102.5 ± 11.5^{B}	133.1 ± 21.9^{C}	$117.8 \pm 23.1^{\#}$
90-degree	242.5 ± 15.5^{F}	174.1 ± 5.3^{E}	$208.3 \pm 37.2^{\wedge}$

Different superscript uppercase letters indicate significant differences among 3D printer-print orientation pairs, while different superscript symbols indicate significant differences among print orientations. Total values are derived from pooled data ($P < 0.05$).

Table 10
Mean ±standard deviation values of measured deviations (μm) for each 3D printer-print orientation pair within nonprepared surfaces.

Print orientation	3D printer		Total
	DLP	SLA	
0-degree	43.7 ± 7.7^{A}	80.7 ± 8.7^{B}	$62.2 \pm 20.8^{*}$
30-degree	93.0 ± 15.1^{C}	98.8 ± 14.0^{CD}	$95.9 \pm 14.3^{\#}$
45-degree	96.4 ± 8.1^{CD}	103.1 ± 7.1^{D}	$99.8 \pm 8.1^{\#}$
90-degree	208.0 ± 9.0^{F}	164.3 ± 2.3^{E}	$186.2 \pm 23.5^{\wedge}$

Different superscript uppercase letters indicate significant differences among 3D printer-print orientation pairs, while different superscript symbols indicate significant differences among print orientations. Total values are derived from pooled data ($P < 0.05$).

Qualitative evaluation of the color maps would facilitate interpreting the differences among test groups by broadening the understanding of measured deviations and potential clinical outcomes caused by them. For the posterior fixed partial denture, DLP-0 casts had a more homogeneous color distribution than those of other 3D printer-print orientation pairs with slightly overcontoured and slightly undercontoured surfaces along with surfaces with acceptable deviations. Slight undercontours were evident on the buccal and occlusal surfaces of both the first premolar and molar teeth; therefore, fixed partial dentures to be seated on DLP-0 may require intaglio surface adjustments for proper fit. For DLP-30, DLP-45, and DLP-90 casts, overcontoured and undercontoured surfaces have started to become dominant on prepared surfaces. Overcontours were visible on the mesial and palatal surface of the first molar in both groups and that of the first premolar in DLP-90 casts; thus, the restorations to be seated on these casts would require more intaglio surface adjustments than those to be seated on DLP-0 casts. SLA-0 and SLA-30 casts differed evidently from their DLP counterparts with a more heterogeneous color distribution on the first premolar and the presence of undercontoured areas on the occlusal surface and overcontoured areas on the palatal surface of the first molar. The color distribution in SLA-45 and SLA-90 casts was similar to their DLP counterparts, while the color distribution of the left first molar crown preparation was mostly similar to that of the right first molar for each group. Regardless of the 3D printer and print orientation, fixed partial dentures to be seated on these casts would also require interproximal contact adjustments to improve fit as overcontours of different magnitudes were visible on adjacent teeth in all casts. However, these adjustments might result in lighter contacts intraorally. Undercontoured surfaces of different magnitudes were visible on the pontic region of these casts and increased build angle constantly increased the magnitude of undercontouring. Any additional veneering on the soft tissue surface of the pontic might cause excessive contacts intraorally and impair cleansability.

For the lateral incisor crown, slight overcontours were evident on the labial and palatal surfaces in DLP-0 and DLP-30 casts, on the palatal surface in DLP-45, SLA-0, SLA-30, and SLA-45 casts, and mesial surface in DLP-90 casts. In addition, the cervical third of the labial surface was slightly overcontoured in SLA-0 casts and the incisal third of the palatal surface was overcontoured in SLA-90 casts. Therefore, intaglio surface adjustments would be required for all crowns to be seated on these casts; however, the duration of these adjustments may change depending on the surface area of the overcontoured surface and its magnitude. In addition, interproximal adjustments may be required on the mesial and distal surfaces of restorations to be seated on DLP-0 and DLP-30 casts and on the distal surface of restorations to be seated on DLP-45, DLP-90, and SLA casts. However, veneering could also be required on the mesial surface of restorations to be seated on DLP-45, DLP-90, and SLA casts. These potential adjustments and additional veneering might also result in light or tight interproximal contacts intraorally.

For the central incisor and canine laminate veneers, overcontoured areas with varying magnitudes were visible on the labial surface or the margins of the preparation in DLP-0, DLP-30, SLA-0, SLA-30, and SLA-45 casts, which indicate a potential need for adjustments on the intaglio surface of veneers to be seated on these casts. However, undercontours with different magnitudes were dominant on the labial surface of the prepared teeth in DLP-45, DLP-90, and SLA-90 casts. These undercontoured areas may impair the retention of the laminate veneers to be seated on DLP-45, DLP-90, and SLA-90 casts.

For the premolar inlay, overcontoured areas of different magnitudes were visible within DLP-fabricated casts as slight overcontours were evident on the palatal wall and palatopulpal line angle of the preparation in DLP-0 and DLP-30 casts, and on the buccal wall and buccopulpal line angle of the preparation in DLP-30, DLP-45, and DLP-90 casts. The magnitude of these overcontoured surfaces was greater in SLA-fabricated casts, and evident overcontours were visible on the buccopulpal line angle in SLA-30, SLA-45, and SLA-90 casts. The pattern of overcontoured surfaces was also visible for the second molar inlay in all casts other than DLP-90 casts, and intaglio surface adjustments of the inlays to be seated on casts with overcontoured surfaces could be potentially needed. However, these adjustments might lead to microleakage intraorally, particularly for those casts with dominant red on the walls and line angles of the inlay cavity preparations.

Qualitative evaluation of the nonprepared tooth surfaces would be beneficial to interpret the potential effect of tested 3D printers and print orientations on the occlusal contacts and esthetics of restorations fabricated on additively manufactured casts. Regardless of the printing technology and print orientation, overcontours with different magnitudes were visible on the occlusal surface of the right second molar and left second premolar. Therefore, adjustments of occlusal contacts during maximum intercuspation are needed for tested casts to better replicate the intraoral situation. In addition, these overcontours were visible on the palatal inclination of the buccal cusps of nonprepared posterior teeth, and adjustments during laterotrusive movements would also be required. However, the duration of these adjustments would be affected by the color distribution and the magnitude of the overcontours. For the anterior region of the casts, all casts except for DLP-90 casts had overcontoured palatal surfaces on anterior teeth. Thus, these areas should be adjusted to replicate the correct protrusive movement of the mandible. Finally, all groups either had overcontoured or undercontoured areas on the labial surface of the anterior teeth. Therefore, any esthetic adjustment of an anterior restoration while using tested casts would potentially require further clinical readjustments.

Previous studies have focused on the comparison between DLP- and SLA-based 3D printers when the fabrication trueness of additively manufactured dentate casts was considered [7,14,16,22–24]. Only one of those studies tested the DLP 3D printer used in this study and showed that the casts fabricated with that 3D printer had a similar intermolar width to that of the master design file [22]. However, a direct comparison between the present and those previous studies on the comparison between DLP- and SLA-based 3D printers might be misleading, given the variability among methodologies, which involve tested 3D printers, reference models, resins, and deviation measurement and evaluation methods. The effect of print orientation on the fabrication trueness of additively manufactured casts has been investigated scarcely, and those studies did not involve 3D printers as a factor [8,18,19,25]. Maneiro Lojo et al. [18] evaluated the accuracy of partially edentulous maxillary casts and concluded that 90-degree print orientation resulted in the lowest trueness when a liquid crystal display (LCD)-based 3D printer was used. Another study also used an LCD-based 3D printer and showed that maxillary implant casts with a single implant at the central incisor region had higher accuracy with 45-degree print orientation compared with 0-degree and 90-degree [8]. In another study on how print orientation (0-degree, 45-degree, and 90-degree) affected the trueness of dentate casts, the effect of print orientation was reported to depend on the tooth type [25]. Ko et al. [19] investigated the combined effect of print orientation (0-degree, 30-degree, 60-degree, and 90-degree) and layer thickness (20 μm, 50 μm, and 100 μm) on the fabrication trueness of dentate maxillary casts while using a DLP-based 3D printer that was not tested in the present study. The authors stated that the casts with 0-degree print orientation and 20 μm layer thickness had lower trueness than those of other casts and associated this result with the potential overpolymerization of excess resin due to bleeding of light through thin layers [19]. The only other study that evaluated how different tooth preparations affected the fabrication trueness when different 3D printers were used solely focused on removable dies [2]. The authors [2] compared DLP, SLA, and fused deposition modeling 3D printers, and concluded that one of the SLA-based 3D printers had the highest trueness followed by one of the DLP-based 3D printers, while different tooth preparations also affected the fabrication trueness within each 3D printer.

Even though 2 well-known and widely used 3D printers were tested in the present study, the number of 3D printers was a limitation. The print orientations tested were deliberately selected to ensure that the support structures were not generated on the dental arch, which is the area of interest. However, different orientations may affect the results. Layer thickness is another adjustable parameter that affects the fabrication trueness [4,7,19], and the standardized layer thickness was another limitation. All casts were fabricated with a standardized base design and manufacturers' proprietary model resins. However, different base designs [3,16] and model resins [17] may affect measured deviations. To minimize and standardize the effect of the digitization process on measured deviations, an industrial scanner was used. However, measured deviations might be amplified in actual clinical situations, considering the accumulative error caused by the intraoral scanner in the direct digital and the conventional impression material and the desktop scanner in the indirect digital workflow, along with patient-related factors. In addition, the absence of a stone control group is a limitation, even though the deviations of those casts would have been biased due to additional errors caused by the conventional impression-making process. The present study did not involve removable dies and tested parameters may affect the fit of the dies in casts along with their fabrication trueness. The deviations were analyzed by using an International Organization for Standardization standard 12836-recommended metrology-grade software program [27]. However, other 3D analysis software programs may affect measured deviations [28]. The present study did not consider the long-term stability of tested casts [17], which could be essential to implement tested 3D printer-print orientation pairs into the clinical routines of dentists and dental technicians. The findings of the present study should be broadened in future studies that involve other 3D printers with different technologies and model resins as well as with studies that evaluate the fit, occlusal contacts, interproximal contacts, and adjustment efficiency of restorations fabricated or adjusted by using these casts.

5. Conclusions

Within the limitations of the present study, the following conclusions were drawn:

1. DLP-based 3D printer and 0-degree print orientation mostly resulted in the highest trueness for posterior tooth preparations and non-prepared tooth surfaces on printed casts. The DLP 3D printer and 30-degree print orientation resulted in the highest trueness for the first premolar inlay and 45-degree print orientation enabled the highest trueness for the central incisor laminate veneer region.
2. The DLP 3D printer irrespective of print orientation, and 30- and 45-degree print orientation regardless of the 3D printer increased the trueness at lateral incisor crown and canine laminate veneer regions in the cast.
3. Of all 3D printer and print orientation pairs, DLP 3D printer and 90-degree print orientation mostly led to the lowest trueness within tested tooth preparations.

CRediT authorship contribution statement

Münir Demirel: Methodology, Investigation, Data curation, Conceptualization. **Almira Ada Diken Türksayar:** Methodology, Investigation, Formal analysis. **Mustafa Borga Donmez:** Writing – original draft, Methodology, Conceptualization. **Burak Yilmaz:** Writing – review & editing, Visualization, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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