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Accuracy evaluation of complete-arch models manufactured by three different 3D printing technologies: a three-dimensional analysis

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Abstract

Purpose: This study aimed to evaluate the trueness and precision of complete-arch models printed with three-dimensional printers via three different printing technologies.

Methods: An arch-shaped master model was designed using software (RapidForm XOR2, 3D Systems Inc., USA), and the digital master model was printed 10 times with three-dimensional printers using stereolithography (SLA), direct light processing (DLP), and Polyjet technology (n = 30). The printed models were then scanned with an industrial scanner to create the respective digital models. All digital models were compared with the master model, and an evaluation of the trueness was performed by model superimposition with Geomagic Control software (3D Systems, Rock Hill, SC, USA). Precision was determined for each case by superimposing some combination of the 10 datasets in each group.

Results: The trueness of the printed models was 46.2 µm for the DLP printer, 51.6 µm for the SLA printer, and 58.6 µm for the Polyjet printer. The DLP models were significantly better than the Polyjet models (p = .005). However, the Polyjet models (30.4 µm) were more precise than the SLA (37.6 µm) and DLP (43.6 µm) models (p < .001, p = .016). Furthermore, the SLA (11.8 µm) was the most accurate printer in the Z-direction (p = .016, p = .002).

Conclusions: The 3D printing technologies showed significant differences in the precision and trueness of complete-arch measurements. Although DLP was more accurate other tested 3D printers, the accuracy of all 3D printed models was within clinical tolerance, and they were clinically acceptable and could be used for the production of fixed restorations.

Keywords: *Rapid prototyping, 3D printing, Direct light processing, Polyjet, Stereolithography*

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1. Introduction

Computer-aided design and computer-aided manufacturing (CAD-CAM) systems have been widely used in dentistry for over 20 years [1]. Due to recent advances in digital technologies, the definitive cast requirement has been eliminated for some CAD-CAM systems [2,3]. However, conventional impressions and definitive casts are still used in the fabrication of prosthetic restorations [3-7].

Definitive casts reproduce the relationships between the prepared abutments of adjacent and opposing teeth [3,8]. At present, definitive casts can be fabricated using subtractive or additive technology. Additive technology is also known as rapid prototyping or three-dimensional (3D) printing, and it is a process in which objects are built layer by layer [9-15]. Currently, this technology is integrated into a digital workflow for dental restorations [9,14,15]. 3D printing is used in different fields of dentistry, such as fixed, removable [15-17], and maxillofacial prostheses in prosthodontics [18], treatment planning in orthodontics [18], surgery, and implant dentistry [19]. 3D printing allows the production of complex objects, shortens manufacturing time, reduces costs [13], and eliminates the need for experienced dental technicians associated with traditional manufacturing [2].

Some commonly used recent technologies for dental 3D printers are stereolithography (SLA), direct light processing (DLP), and material jetting (Polyjet) [15,20]. SLA printers use an ultraviolet (UV) laser to cure photosensitive liquid polymers [12,20]. This curing process is repeated layer-by-layer until the CAD design is completed. Smooth and fine surface details and high accuracy are the advantages of SLA technology. However, the production costs are higher than those of other 3D printing technologies [12]. DLP printers use high-power LEDs and photosensitive resin materials to build layers. DLP devices use individually moving micromirrors to control light reflections. These micromirrors correspond to each pixel of the image, and the building time of the object is minimized [12]. Polyjet or material jet technology uses materials extruded from nozzles, or a photopolymer jetted over the workspace, and then the object is polymerized with a UV light source [12,15].

Accuracy consists of two parameters: trueness and precision. The trueness of a 3D printer is described as the deviation of the printed object from its actual dimensions, and the precision of a 3D printer is the deviation between repeated prints [5,21]. High trueness describes the proximity to the original dimensions of the measured object, and high precision defines a 3D printer's ability to manufacture the same product with the same dimensions in repetitive prints [22]. Although there are some studies on the accuracy of printed objects, the number of studies related to the accuracy of 3D printed working models is limited in the literature [23-25].

This study aimed to evaluate the accuracy of the trueness and precision of the models used for the production of fixed restorations that were printed with three different 3D printing technologies. The null hypothesis was that no statistically significant differences exist between models fabricated using three different 3D printers.

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2. Materials and methods

An arch-shaped master model to simulate the mandibular arch (14 mm in height and 16 mm in width) was designed with CAD software (RapidForm XOR2; 3D Systems). Six abutments with a 6º total angle of convergence and 1 mm at the circumferential shoulder finish lines were produced to resemble prepared teeth (right mandibular second molar, right mandibular second premolar, right mandibular canine, left mandibular canine, left mandibular second premolar, and left mandibular second molar) with a height of 10.15 mm placed on the arch . Cross marks were added at the middle of each abutment's occlusal surface and were used as reference points to allow measurements of the X, Y, and Z coordinates.

Then, the digital master model (DMM) was saved in Standard Tessellation Language (.stl) format and transferred to each of the 3D printers. Ten models were manufactured by each printer using three different printing technologies: SLA technology (Ultra SP Ortho, envisionTEC), DLP technology (Perfactory Vida, envisionTEC), and Polyjet technology (Objet30 Prime, Stratasys Ltd.) (Fig. 1). A total of 30 models were printed. The technical details of the 3D printers are summarized in Table 1. The printer technology, support materials, post-process, manufacturing time, and costs are given in Table 2.

2.1. Scanning procedure

An industrial structured blue LED light 3D scanner (ATOS Core 200 5M, GOM GmbH, Braunschweig, Germany) was selected as the reference scanner (RS). The RS was calibrated and tested according to VDI/VDIE 2634 Part 3 (VDI e.V.; Düsseldorf, Germany), displaying maximum deviations of 0.002 mm probing error form (sigma), 0.004 mm probing error (size), 0.007 mm sphere spacing error, and 0.008 mm length measurement error. Then, the printed models were scanned with the RS and each model was created using a digital printed model (DPM). DPMs were saved in .stl file format.

2.2. 3D Analysis

3D analysis software (Geomagic Control, 3D Systems) superimposed the DPM over the DMM using the best-fit alignment method, and the same method was used for each DPM. A sample size of 15,000 points with a tolerance of 0.001 mm was used in the 3D analysis. The root mean square (RMS) and average maximum and minimum values were displayed in the software. Trueness was assessed, in each case, by the superimposition of the DMM data on the datasets obtained from the SLA, DLP, and Polyjet DPMs.

Precision was determined for each model by superimposing combinations of the 10 datasets in each group (45 pairs for each printer technology) (for example, for the ten SLA DPMs: 1 with 2/3/4/5/6/7/8/9/10, 2 with 3/4/5/6/7/8/9/10, 3 with 4/5/6/7/8/9/10, 4 with 5/6/7/8/9/10, 5 with 6/7/8/9/10, 6 with 7/8/9/10, 7 with 8/9/10, 8 with 9/10, 9 with 10).

At the last stage, the coordinates of the reference marks on the DPMs were calculated and compared with the reference marks on the DMM, using the comparison point algorithm to show the magnitude of the movements away from exact positions in the X, Y, and Z directions. The positive and negative values of the X, Y, and Z coordinates indicated movement away from the initial positions. The X coordinate values indicated buccolingual movement, Y values indicated mesiodistal movement, and Z values indicated occlusogingival movement.

Color-coded maps were used to evaluate the distribution of three-dimensional deviations over the complete surface of each DPM. In the color-coded maps, the yellow-to-red fields indicate that the DPMs were larger than the DMM, and light blue-to-dark blue fields indicated that the DPMs were smaller than DMM.

2.3. Statistical analysis

Statistical analysis was performed with a significance level of 95% using software (SPSS v20 for Macintosh; IBM Corp.) (IBM Corp., Armonk, NY, USA). For trueness values, a one-way ANOVA was used to evaluate group differences, and the post-hoc Tukey HSD test was used for multiple comparisons of group differences. For precision values, the Kruskal-Wallis and Dunn tests were performed to evaluate statistical differences. The one-way ANOVA and post-hoc Tukey HSD tests were used to show significant differences between the movements in the X, Y, and Z directions.

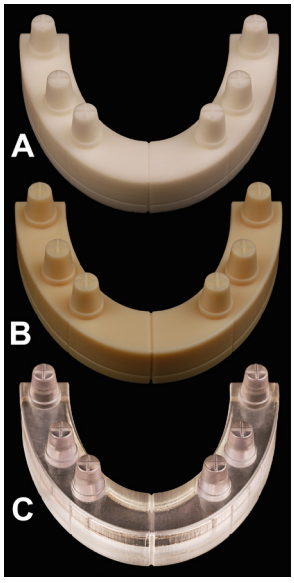


Fig. 1. Printed models used in this study. A: SLA, B: DLP, C: PolyJet.

3. Results

3.1. Trueness

The comparison of trueness measurements for the three different technologies presented significant differences. The mean trueness was 51.6 µm for the SLA models, 46.2 for the DLP models, and 58.6 µm for the Polyjet models (Table 3). The DLP models were closer to master model than Polyjet models. The trueness value differences between the DLP and Polyjet models were found statistically significant (p=.005) (Table 4).

3.2. Precision

There were significant differences in the mean RMS values of precision of printed models between all technologies . The mean precision was 37.6 for the SLA models, 43.6 µm for the DLP models, and 43.6 µm for the Polyjet models (Table 5). The Polyjet models were more precise than the SLA and DLP models. The difference found from the comparison between Polyjet-SLA (p<.001) and Polyjet-DLP (p=.016) models were statistically significant (Table 6).

3.3. Reference mark assessment

According to a comparison between the reference marks on the printed models (Table 7), no statistically significant differences were observed in the X- (p=.079) or Y-direction (p=.567); only the Z-direction showed significant differences (p=.002) (Table 8). The SLA models showed the most accurate results (p=.016 and p=.002) in the Z-direction (Table 9).

3.4. Color-coded map assessment

According to the color-coded maps for the SLA DPMs, a slight contraction was observed on the buccal surfaces of the abutments and the arch. In addition, on the finish lines of the abutments, circumferential shrinkage was detected. However, the lingual surfaces of the posterior abutments and the coronal surface of the arch represented a slight expansion (Fig. 2). The DLP DPMs displayed a homogenous pattern of

Table 1. Technical details of tested printers.

Model	Manufacturer	Technology	Material	Layer Thickness	Resolution (x-,y- and z-axis)	Building envelope
ULTRA 3SP Ortho	envisionTEC	3SP (Scan, spin, selectively photocure) SLA (Stereolithography)	ABS Tough	50 µm	X&Y - 100 µm Z - 50 to 100 µm	266 x 175 x 76 mm
Perfactory Vida	envisionTEC	DLP (Direct light processing)	E-Model	50 µm	X&Y - 73 µm Z - 25 to 150 µm	140 x 79 x 100 mm
Objet30 Prime	Stratasys	PolyJet	VeroClear	16-28 µm	X-axis: 600 dpi Y-axis: 600 dpi Z-axis: 1600 dpi	294 x 192 x 148.6 mm

Table 2. Production time and manufacturing costs of tested printers.

Model	Support Material	Time for post cure	Time for post process	Production time	Cost of one model
Ultra 3SP Ortho	No need	3 min	2 min (isopropanol alcohol bath)	18 models in 1 hour	$ 2-9
Perfactory Vida	No need	3 min	2 min (isopropanol alcohol bath)	4 models in 1 hour	$ 2-9
Objet30 Prime	SUP705	No need	2 min (waterjet)	4 hr, 10 min (one model)	$ 12,5

Table 3. Trueness values (µm) for all DPMs.

	Mean	Std. deviation	Min	Max.
SLA	51.6	7.99	40.4	64.8
DLP	46.2	9.86	36.8	66.3
PolyJet	58.6	5.60	51.7	68.5

Table 4. Mean (Trueness) RMS differences of DPMs compared with the master model and results of Tukey HSD post-hoc test.

Model		Mean Difference	Sig.
SLA	DLP	5.32	.314
	PolyJet	-7.01	.143
DLP	SLA	-5.32	.314
	PolyJet	-12.33	.005
PolyJet	SLA	7.01	.143
	DLP	-12.33	.005

Table 5. Precision values (µm) for all DPMs.

	Mean	Std. Dev.	Min	Max.
SLA	37.6	11.46	18.4	60.3
DLP	43.6	13.77	15.1	73.7
PolyJet	30.4	9.34	11.4	57.1

Table 6. Statistical outcome of (precision) Kruskal-Wallis test.

Model	Test Statistic	Adj. Sig.
SLA-DLP	-17.22	.110
SLA-PolyJet	22.92	.000
DLP-PolyJet	40.14	.016

Table 7. Mean differences (µm) of all DPMs on X, Y and Z-directions.

Direction	Model	Mean	Std. deviation	Min	Max
X	SLA	0.02	0.12	0	1
	DLP	0.48	2.08	0	12
	PolyJet	0.08	0.27	0	1
Y	SLA	0.17	0.45	0	2
	DLP	0.53	3.12	-2	24
	PolyJet	0.35	0.79	0	4
Z	SLA	11.83	10.06	0	33
	DLP	18.08	13.96	1	54
	PolyJet	19.53	12.51	1	60

Table 8. ANOVA results of differences between reference marks on DPMs and DMM and discrepancies on X, Y, and Z coordinates.

		df	F	Sig.
X	Between Groups	2	2.577	.079
	Within Groups	177		
	Total	179		
Y	Between Groups	2	.569	.567
	Within Groups	177		
	Total	179		
Z	Between Groups	2	6.652	.002
	Within Groups	177		
	Total	179		

Table 9. Post-hoc test results (µm) of DPMs on X, Y and Z-directions.

Direction	Model		Mean Difference	Sig.
X	SLA	DLP	-0.46	.093
		PolyJet	-0.60	.952
	DLP	SLA	0.46	.093
		PolyJet	0.40	.173
	PolyJet	SLA	0.60	.952
		DLP	-0.40	.173
Y	SLA	DLP	-0.36	.536
		PolyJet	-0.18	.855
	DLP	SLA	0.36	.536
		PolyJet	0.18	.855
	PolyJet	SLA	0.18	.855
		DLP	-0.18	.855
Z	SLA	DLP	-6.25	.016
		PolyJet	-7.70	.002
	DLP	SLA	6.25	.016
		PolyJet	-1.45	.795
	PolyJet	SLA	7.70	.002
		DLP	1.45	.795

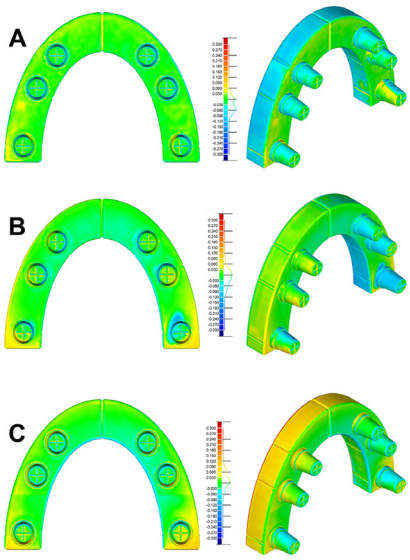


Fig. 2. Color-coded maps of DPMs (Trueness). Yellow through red color code indicates that, DPM is larger than master model; light blue through dark blue color code indicates that, DPM is smaller than DMM; green surfaces present that deviations ranged between 0 to ±30 µm. A: SLA, B: DLP, C: PolyJet.

green surfaces, but a slight expansion was observed on the posterior side and a slight contraction was observed on the lingual surface of the arch. In contrast to the lingual surfaces, the buccal surfaces of posterior abutments displayed expansion. For Polyjet DPMs, the buccal surface of the arch generally appeared to be larger than the master model. A circumferential expansion was observed on the finish lines of the abutments. However, the lingual surfaces of the abutments presented a slight shrinkage (Fig. 2).

4. Discussion

According to the results of the present study, the different 3D printing technologies showed significant differences in terms of trueness and precision. Therefore, the null hypothesis of the study was rejected. The DLP DPMs showed significantly lower mean values for trueness (p=.005) than the Polyjet DPMs. However, the Polyjet DPMs showed higher precision than SLA and DLP (p<.001 and p=.016). In the Z-direction, the SLA DPMs were more accurate than the DLP and Polyjet DPMs (p=.016 and p=.002).

3D printing technologies can fabricate various objects with different geometries using suitable materials for dentistry. In addition, differences in the tolerance values of the manufacturing processes will naturally depend on different clinical applications [18]. The clinically acceptable limits for evaluating the accuracy of the working models is related to dental treatments [13]. The accuracy of the working models might affect the misfit of fixed prostheses, which could lead to larger marginal or internal discrepancies before the delivery of the prosthesis [3,26]. Previous studies have shown varying results for the clinically acceptable limit of misfit. The clinically acceptable discrepancy for fixed dental prosthesis varies between 100 and 150 µm [27-32]. In this study, the trueness of all printed working models was found to be below 100 µm and was considered clinically acceptable. In the present study, the mean RMS trueness values were 51 µm for SLA, 46 µm for DLP, and 58 µm for Polyjet. The DLP DPMs were more accurate than the Polyjet DPMs, although the layer thickness of the Polyjet printer (16 µm) was thinner than DLP printer (50 µm). In this study, the Z-axis resolution of Polyjet (16 µm) was higher than that of DLP (50 µm). According to Brain et al. [18], high resolution is not equivalent to accuracy. Printers that have high resolution can manufacture models with fine details, but printed materials may not be sufficiently accurate. Furthermore, in the scanning process, a thin layer of scan spray was applied to the Polyjet DPMs because of the transparent structure of the VeroClear printing material. The deviations observed on the Polyjet DPMs might arise from the thickness of the scan spray, which might have affected the accuracy of Polyjet DPMs.

After the 3D analysis process, the analysis software gives 3D deviation data that consist of RMS, average (+) and average (-) values. In this study, the RMS values preferred instead of the average (+) and average (-) values. Because in quantitative evaluation, if the average (+) and average (-) deviations have an equal distribution, the total deviation values will be close to zero. [3,33-35]. In addition to the comparison of RMS values, a qualitative inspection of color-coded maps was also needed to evaluate the distribution of deviations [3,35]. The color-coded maps of DLP DPMs displayed a more homogenous pattern of green areas than SLA and Polyjet, which shows that the dimensions of the DLP models are nearly the same size as the master model. On most of the abutments of all the models (SLA, DLP, and Polyjet), a slight contraction was observed. This contraction on the posterior abutments might have been due to the higher photopolymer density in the posterior than in the anterior region[36]. A homogenous pattern of blue surfaces (contraction) on the buccal side of the arch was observed in the color-coded map of the SLA models. These areas have a smooth surface, and this allows the polymers to contact evenly [36]. Therefore, the reason for the contraction might be polymerization-induced shrinkage. In the color-coded maps, the Polyjet models displayed a slight expansion on the buccal side of the arch. The reason for this might also be the expansion of resin during the printing process.

Factors such as layer thickness [37], number of layers, model shrinkage [23], laser speed, intensity [22], angle, building direction [38], and post-processing [23] can affect the trueness and precision of printed objects, and this causes differences in the production of the final model [22]. Comparing our results with those of other studies is challenging, because the reference scanners, materials, master model geometries, printing technologies, printer parameters, 3D analysis software, and methodology used in these studies were varied. For this reason, partial comparisons were made for some parameters.

Jeong et al. [39] used RMS values to evaluate half-arch models and found that SLA models (52 µm) were more accurate than milled models (152 µm). Brain et al. [18] used two different master models with different geometries and manufactured them with four different 3D printers. The accuracy of all printed models was found to be below 100 µm. Kim et al. [13] found the accuracy of full-arch master models to be 176 µm for SLA, 74 µm for DLP, and 69 µm for Polyjet printers. Additionally, the Polyjet and DLP models were found to be more precise than the SLA. In the study by Kim et al. [13], the layer thickness and X-Y resolution values of SLA and DLP printers were different from that of the current study. On the other hand, the accuracy of the Polyjet printer (69 µm) was close to that of the present study. Jin et al. [26] also used RMS values for the evaluation process and mean trueness of complete-arch SLA, and Polyjet models were found to be 114.3 µm and 124 µm, respectively. The reason for this difference might be the more complicated geometry of the master model and different brands of printers. The mean RMS precision values were 59.6 µm for the SLA models and 41 µm for the Polyjet models. In the current study, mean RMS precision values were 37 µm for SLA, 43 µm for DLP, and 30 µm for Polyjet. These values were close to the precision values of this study, and slight differences can occur between different printers and printing materials. According to Jin et al. [26] The higher precision of Polyjet can be explained by the new photopolymer resin cartridge. Polyjet produces objects with unused photopolymer in every manufacturing process; however, non-polymerized resins stored in the SLA printer's tank are repeatedly used, and the phase change of the photopolymer resin may cause flaws during the curing process. In the present study, SLA was the most accurate printer in the Z-direction among the tested printers. Lee et al. [40] stated that the X - and Y-direction direction accuracies were better than that of the Z-direction. Many parameters, such as material evaporation, shrinkage, and warping during the curing process that are difficult to control, could affect the accuracy of the Z-direction. The reason for the Z-direction accuracy maybe the patented 3SP (scan, spin, selective photocure) technology, which is different from that of conventional SLA printers. The costs and printing speeds of devices with different 3D printing technologies varies. In the current study, high-end 3D printers from

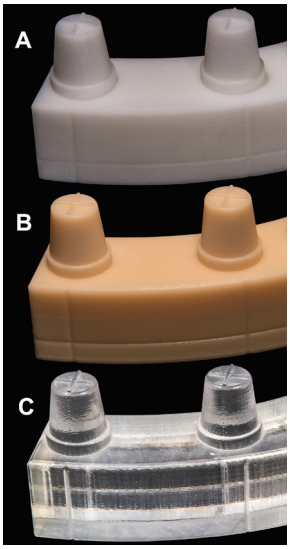


Fig. 3. Close view of printed models. A: SLA, B: DLP, C: PolyJet. No signs of stair stepping on buccal and lingual surfaces.

well-known brands that had comparable market prices selected. The costs and printing time of one model varied according to the printer technology (Table 2). The SLA device prints eighteen models in 1 h, DLP prints four models in 1 h, and Polyjet prints one model in 4 h. The reason for the fast production speed of the SLA device may be the light-curing technology. Although the printing speeds of the printers were different, the surface finish quality of the SLA, DLP, and Polyjet DPMs were similar. (Fig. 3). This study had a few limitations. Only three types of 3D printers and printing materials were evaluated. The master model and abutments were designed with a less complicated morphology than a natural arch and natural teeth. 3D printing is used to manufacture physical casts following intraoral scanning in prosthetic dentistry. Different steps used in the 3D manufacturing process, such as printing technology, post-processes, printing parameters, and suitable materials for dentistry should be included in future studies to evaluate the effect on physical dental casts.

5. Conclusion

Within the limitations of this study, in comparison of the STL reference files,the DLP DPMs showed higher trueness than the Polyjet. However, the Polyjet DPMs were more precise than SLA and DLP. Additionally, SLA DPMs were more accurate than other printers in the Z-direction. In trueness measurements, the dimensional deviation value observed across the whole master model was a maximum of 68.5 µm. The current study demonstrated that the dental models manufactured with tested 3D printers were within clinical tolerance and may be appropriate for the production of fixed restorations. Therefore, dentists or dental technicians should choose a suitable printer according to cost-effectiveness or the most important value that is needed for the clinic, study, or laboratory.

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