Original Article

Optimization of three-dimensional printing parameters for orthodontic applications

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ABSTRACT

Objectives: To determine the impact of build orientation, increased layer thickness, and dental crowding on the trueness of three-dimensional (3D)–printed models, and to evaluate how these parameters affect the fit of thermoformed appliances.

Materials and Methods: Ninety-six dental models were printed horizontally and vertically on the building platform using different 3D-printing technologies: (1) a stereolithography (SLA) printer with layer thicknesses of 160 μm and 300 μm and (2) a digital light processing (DLP) printer with layer thicknesses of 100 μm and 200 μm. Each printed model was digitalized and superimposed on the corresponding source file using 3D rendering software, and deviations were quantified by the root mean square values. Subsequently, a total of 32 thermoformed appliances were fabricated on top of the most accurate 3D-printed models, and their fit was evaluated by digital superimposition and inspection by three blinded orthodontists. Paired *t*-tests were used to analyze the data.

Results: Significant differences ($P < .05$) between printing technologies used were identified for models printed horizontally, with the SLA system achieving better trueness, especially in crowded dentitions. No significant differences between technology were found when models were printed vertically. The highest values of deviation were recorded in appliances fabricated on top of DLP-printed models. The results of the qualitative evaluation indicated that appliances fabricated on top of SLA models outperformed the DLP-modeled appliances.

Conclusions: Three-dimensional printing with increased layer height seems to produce accurate working models for orthodontic applications. (*Angle Orthod*. 2024;94:375–382.)

KEY WORDS: 3D print; Stereolithography; Digital light processing; Orthodontics

INTRODUCTION

Three-dimensional (3D) printing currently plays an increasing role in facilitating in-house production of working models required for the fabrication of clear aligners and retainers. There are many types of 3D-printing technology for rapid prototyping; however, the vast majority of orthodontic practices use either stereolithography (SLA) or digital light processing (DLP) printers. Both SLA and DLP are categorized as an "additive manufacturing process" in which the 3D object is produced by adding layers of liquid resin followed by their exposure to light to initiate polymerization. The primary difference between the two types of technology is that DLP printers use a light projector that photopolymerizes the entire layer all at once, which makes the process faster.[1]

The number of layers required to print an object has a direct effect on printing speed and quality; that is, the smaller the layer thickness (also called the Z-layer), the longer it takes to complete a print, but the higher the quality of the prototype. Reduced layer thickness also leads to higher prices because of the need to deposit more layers of material. Loflin et al.[2] investigated the influence of three layer thicknesses (25, 50, and 100 μm) on the accuracy of diagnostic models and reported that 3D-printed models with a layer height of 100 μm are potentially clinically acceptable for diagnostic purposes; however, only a

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Accepted: February 2024. Submitted: October 2023.
Published Online: April 9, 2024

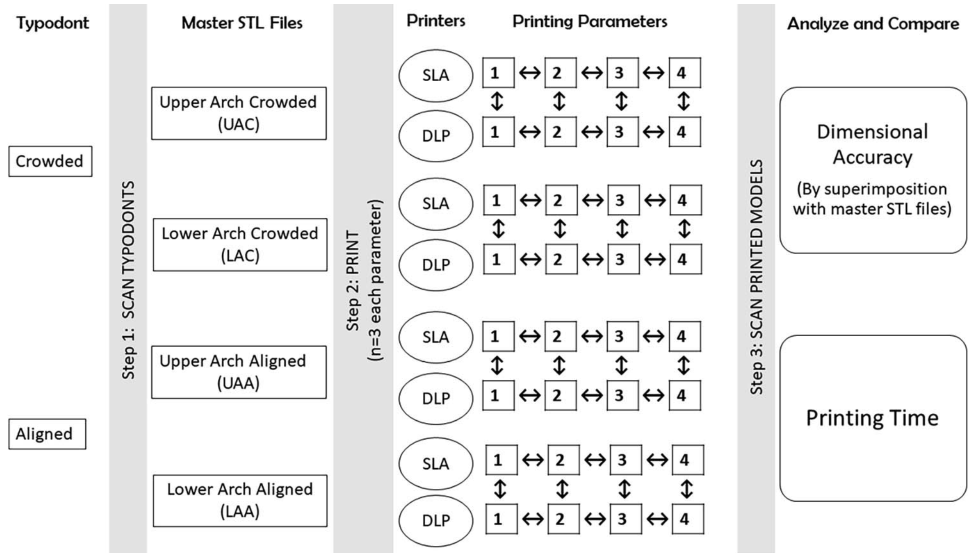

Figure 1. Experimental design for aim 1. Description of the printing parameters 1 to 4 in the stereolithography (SLA) and digital light processing (DLP) printers are found in Table 1.

single SLA printer was used in the study, and all diagnostic models were printed with a full base, which may not be necessary for working models. Camardella et al.[3] focused on the accuracy of printed models with different model bases and concluded that a horseshoe-shaped base with a bar connecting the molars allows for accurate reproduction of the digital file. Another factor that affects accuracy and speed is the orientation of the models in the building chamber. Models oriented parallel to the printer platform take less time to print than models oriented vertically because the total number of layers required to reproduce the object is significantly reduced.[1,4] In summary, when selecting the appropriate digital workflow in orthodontics, account must be taken of the printing system, clinical condition, and the desired accuracy of the printed object. Therefore, the aims of the study were twofold: (1) to evaluate the effect of build orientation, increased layer thicknesses, and dental crowding on the trueness of 3D-printed models using SLA and DLP printers and (2) to investigate the fit of thermoformed appliances (TAs) shaped on top of aligned and crowded models prototyped with increased Z-layer heights and different orientations. It was hypothesized that accurate orthodontic working casts could be manufactured using layer thicknesses of 100 to 300 μm.

MATERIALS AND METHODS

Two typodonts were selected as the sources of stereolithography (STL) files: one typodont contained a complete, aligned permanent dentition (Paradigm, OR-01, Escondido Calif), whereas the other showed a crowded Class I malocclusion (Paradigm, OR-07A). The digital models were obtained by scanning the typodonts with an intraoral Trios scanner (3Shape, Copenhagen, Denmark) to mimic the actual clinical setting. The original files were exported to Appliance Designer Software (3Shape) to design hollow dental models with horseshoe-shaped bases and posterior bars connecting the second molars. A total of four master STL files were obtained: an upper arch aligned (UAA), a lower arch aligned (LAA), an upper arch crowded (UAC), and a lower arch crowded (LAC).

The research design for aim 1 is summarized in Figure 1. Briefly, each STL master file was used to generate dental casts using two different printers: an SLA printer (Form 3, Formlabs, Somerville, Mass) and a DLP 3D printer (MiiCraft Ultra, Miicraft, Taiwan). Different layer thicknesses (Z-axes) were tested in combination with two different orientations of the dental casts relative to the printer platform. The master STL files (UAA, LAA, UAC, LAC) were printed separately and manufactured in triplicate using four different printing parameters for each system as described in Table 1. The triplicate printing was important to reduce random error and to generate multiple data points for statistical comparisons. Resolution settings in the SLA printer were 160 and 300 μm, with 160 μm being the highest resolution. In the DLP

Table 1. Printing Parameters Evaluated in This Study

	Stereolithography Printer		Digital Light Processing Printer	
Parameter	Z-Layer, μm	Cast Orientation	Z-Layer, μm	Cast Orientation
1	160	Horizontal	100	Horizontal
2	160	Vertical (80°)	100	Vertical (80°)
3	300	Horizontal	200	Horizontal
4	300	Vertical (80°)	200	Vertical (80°)

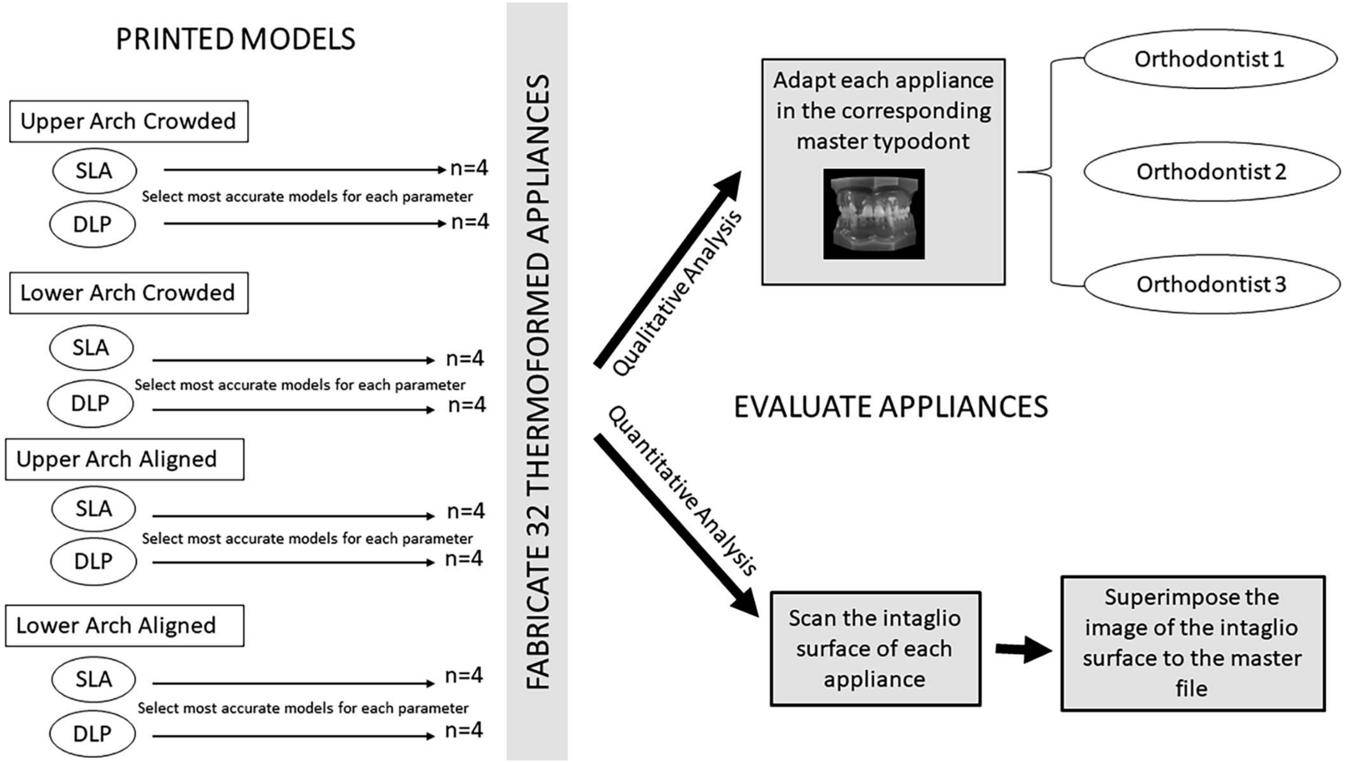

Figure 2. Experimental design for aim 2.

printer, the highest resolution setting was 100 μm and the lowest was 200 μm. Each model was printed in two orientations: horizontal and vertical with an angulation of 80° relative to the printer base. Supports were generated automatically by the software. The resins used for SLA 3D printing were Grey and Draft (Formlabs Inc) for the 160-μm and 300-μm layer thicknesses, respectively. The polymers for DLP printing were KeyModel Ultra and KeyOrthoModel (Keystone Industries, Gibbstown, NJ) for the 100-μm and 200-μm layer thicknesses, respectively. All dental models were printed and processed according to the manufacturer's recommendations.

The 96 printed models were digitalized with the use of a desktop scanner (E-3, 3Shape, Copenhagen, Denmark). To analyze the dimensional accuracy, the STL file of the printed model was superimposed on the corresponding master STL file using a best-fit algorithm in 3D rendering software (Geomagic Control X; 3D Systems, Rock Hill, SC). Superimpositions of five random files were performed twice to confirm the software reproducibility. Briefly, the distance between each measured surface point of the STL master file to the surface of the corresponding STL test file was calculated in the X, Y, and Z coordinates. Deviations were reported in millimeters, with the color map range set to 1.5 mm and −1.5 mm with a tolerance of 0.1 mm (100 μm). The deviations between the tested model and the reference scan were quantified by the root mean square (RMS), which is a measure of the magnitude of all deviations. The lower the RMS value, the more accurate the prototype when compared with the master STL file.

For aim 2 (Figure 2), TAs were fabricated using the MiniStar S with Scan Technology (Great Lakes, Tonawanda, NY) and the thermal forming material Clear Splint Biocryl 0.75 mm/125 mm round (Great Lakes). A total of 32 TAs were fabricated on top of the most accurate 3D-printed models, representing each combination of resin, arch, tooth arrangement, and orientation as determined by aim 1. All appliances were fabricated by a single investigator using a new machine with advanced thermostatic heating technology to minimize operator-induced error. Quality control was achieved with independent evaluations by three blinded orthodontists. Briefly, the TAs were positioned by each orthodontist on the master typodonts and evaluated according to the following criteria: (1) self-retention, (2) stability, (3) proximity of the plastic to the anterior teeth, (4) proximity of the plastic to the posterior teeth, and (5) overall quality.[5] A four-point rating scale was used to evaluate each category, with "1" being the best rating and "4" being the poorest rating. For quantitative analysis, the intaglio surfaces of the TAs were sprayed with an opaque powder, and the appliances were digitalized with the use of a desktop scanner (E-3, 3ShapeCopenhagen, Denmark). The STL files were then imported into Geomagic Control X software for superimposition. A measure of fit

Table 2. Root Mean Square (RMS) and Printing Time Mean Values of the Three Replicates for Each Parameter (Z-Layer in μm, Orientation) in the Stereolithography (SLA) and Digital Light Processing (DLP) Printers[a]

	SLA Printer				DLP Printer		
	Typodont	Printing Time, min	RMS		Typodont	Printing Time, min	RMS
Parameter 1 (160, H)	UAC	54	0.1077	Parameter 1 (100, H)	UAC	37	0.2066
	LAC	43	0.1345		LAC	35	0.1825
	UAA	46	0.1774		UAA	35	0.1796
	LAA	38	0.1715		LAA	30	0.1681
Parameter 2 (160, V)	UAC	93	0.1275	Parameter 2 (100, V)	UAC	107	0.1515
	LAC	77	0.1123		LAC	93	0.1463
	UAA	82	0.1090		UAA	98	0.1793
	LAA	72	0.1432		LAA	91	0.1751
Parameter 3 (300, H)	UAC	37	0.1036	Parameter 3 (200, H)	UAC	20	0.3217
	LAC	22	0.1592		LAC	19	0.3236
	UAA	24	0.1219		UAA	19	0.2490
	LAA	30	0.2635		LAA	17	0.2383
Parameter 4 (300, V)	UAC	49	0.1517	Parameter 4 (200, V)	UAC	58	0.2185
	LAC	41	0.2086		LAC	51	0.2101
	UAA	41	0.1947		UAA	56	0.2031
	LAA	38	0.3039		LAA	49	0.2398

[a] H indicates horizontal; LAA, lower arch aligned; LAC, lower arch crowded; UAA, upper arch aligned; UAC, upper arch crowded; V, vertical (80°).

was determined by the mean of all calculated positive (+Avg) and negative (−Avg) gap distances between the intaglio surface of each appliance and its respective digital model.

Statistical Analysis

The sample size of this study had 80% power to detect an effect size as low as 1.2 SD for between-printer comparison and 1.75 SD for within-printer comparison for an alpha level of .05. Paired *t*-tests were conducted to determine which printer and which parameter setting was optimal. Further exploratory analysis was performed to compare between the upper and lower arches and between typodont types to determine whether printing results were influenced by arch location or dental crowding. Differences were considered significant if $P < .05$. All statistical analyses were performed using SAS v9.4 (SAS Institute, Cary, NC).

RESULTS

The "RMS" and "Printing Time" values reported in Table 2 correspond to the mean of the three technical replicates for each master file (UAA, LAA, UAC, LAC) using the four proposed parameters for each printer previously presented in Table 1. As expected, models printed horizontally (H) on the building plate required less printing time. Parameter 4 (300, V) in the SLA printer provided the fastest print speed in the vertical orientation, whereas Parameter 3 (200, H) in the DLP printer provided faster printing times in the horizontal orientation. The results in Table 3 show the overall differences between systems, clinical conditions, dental arches, orientation, and Z-layer heights. By and large, models printed vertically produced better prints than horizontally printed models with mean RMS values of 0.18 ± 0.06 and 0.19 ± 0.07, respectively.

The trueness of printing parameters in the SLA printer is shown in Table 4. There were significant differences in the mean RMS values among the four typodonts for printing parameters (P) 1, 3, and 4. At the 160-μm layer thickness printed horizontally (P1), the UAC typodont showed a significantly lower RMS

Table 3. Overall Root Mean Square (RMS) Values (Mean ± SD) and Comparison of RMS Values Between Printing Systems, Clinical Conditions, Dental Arches, Orientation, and Z-Layer Heights

	Printing System		
	Digital Light Processing (DLP)	Stereolithography (SLA)	*P* Value
RMS	0.21 (0.06)	0.16 (0.07)	<.0001*
	Clinical Condition		
	Crowded	Aligned	
RMS	0.18 (0.07)	0.19 (0.06)	.1515
	Arch		
	Upper	Lower	
RMS	0.18 (0.06)	0.20 (0.07)	.0664
	Orientation		
	Horizontal	Vertical	
RMS	0.19 (0.07)	0.18 (0.06)	.0074*
	Lower Z-Layers		
	100 μm (DLP)	160 μm (SLA)	
RMS	0.17 (0.03)	0.14 (0.03)	.0004*
	Higher Z-Layers		
	200 μm (DLP)	300 μm (SLA)	
RMS	0.25 (0.05)	0.19 (0.08)	<.0001*

* $P < .05$, paired *t*-test.

Table 4. Mean (SD) Root Mean Square (RMS) Values for Each Printing Parameter (Z-Layer in μm, Orientation) in the Stereolithography (SLA) Printer[a]

SLA Printer Parameter (P)	Typodonts				*P* Values for Comparisons			
	UAC	LAC	UAA	LAA	UAC vs UAA	LAC vs LAA	UAC vs LAC	UAA vs LAA
P1 (160, H)	0.11 (0.01)	0.13 (0.02)	0.18 (0.03)	0.17 (0.03)	**.0185***	.2034	.3561	.8392
P2 (160, V)	0.13 (0.01)	0.11 (0.01)	0.11 (0.00)	0.14 (0.03)	.5236	.2867	.5986	.2398
P3 (300, H)	0.10 (0.03)	0.16 (0.02)	0.12 (0.01)	0.26 (0.03)	.5273	**.0006***	.0579	**.0000***
P4 (300, V)	0.15 (0.01)	0.21 (0.06)	0.19 (0.04)	0.30 (0.12)	.1403	**.0015***	.0523	**.0003***

[a] H indicates horizontal; LAA, lower arch aligned; LAC, lower arch crowded; UAA, upper arch aligned; UAC, upper arch crowded; V, vertical (80°).
* $P < .05$, paired *t*-tests.
Asterisk and bold fonts indicate statistically significant differences.

value compared with the UAA typodont. At the 300-μm layer thickness printed both horizontally and vertically (P3 and P4), there were significant differences between the LAC and LAA typodonts as well as between the UAA and LAA typodonts. By and large, the crowded dentition achieved lower RMS values than the aligned dentition did for most parameters in the SLA system. In the DLP technology (Table 5), there were no statistically significant differences in mean RMS values among the four typodonts for printing parameters 1, 2, and 4. Parameter 3 (200, H) was the only one that showed a statistically significant difference, with crowded typodonts achieving higher RMS values than aligned typodonts.

Table 6 shows the comparisons of RMS values between SLA and DLP printers. The lowest RMS value of 0.11 ± 0.02 was observed in the UAC typodont printed horizontally using the SLA system. Statistically significant differences between the printing technologies were found for the UAC, LAC, and UAA typodonts when printed horizontally, with the SLA system achieving lower RMS values. The mean RMS values of all typodonts did not differ significantly according to the type of technology when printed vertically. The color map in Figure 3 shows the deviation patterns between the DLP-printed models and their respective master models when printed horizontally. In the SLA technology, most values were contained within the tolerance range of 0.1 mm.

The bar charts in Figure 4 show +Avg deviations ± SD (mm) and −Avg deviations ± SD (mm) between the intaglio surfaces of the TAs and their respective digital models. When considering areas of expansion (+Avg), there were no significant differences between the two systems (DLP vs SLA) for TA fit on the dental cast (Figure 4A). For areas of contraction (−Avg), the highest values of deviation were recorded in TAs fabricated on top of LAA and LAC DLP-printed models, which performed significantly worse than the lower TAs from the SLA group (Figure 4B). The acceptability of the appliance fit over the master typodonts was high among the three blinded evaluators (Table 7). Qualitative evaluations between the printing systems found that TAs fabricated on top of SLA models outperformed the DLP modeled TAs in their retention, stability, anterior coverage, and posterior coverage. Four appliances out of 16 fabricated over DLP-printed models scored poorly among the three blinded orthodontists.

DISCUSSION

Managing speed and accuracy efficiently is crucial to ensure a productive digital workflow in orthodontics. Previous studies[6–9] evaluating the trueness or precision of 3D-printed dental models using SLA and DLP printers indicated that a 100-μm layer thickness appears to be adequate for orthodontic purposes when compared with resolutions of 25, 50, and 75 μm, which had slower print times. The main goal of this project was to evaluate the performance of 3D-printed models with increased layer thicknesses. The breadth of this study, encompassing the integration of 3D-printing technology, printing parameters, and the quality of the final appliances, made it

Table 5. Mean (SD) Root Mean Square (RMS) Values for Each Printing Parameter (Z-Layer in μm, Orientation) in the Digital Light Processing (DLP) Printer[a]

DLP Printer Parameter (P)	Typodonts				*P* Values for comparisons			
	UAC	LAC	UAA	LAA	UAC vs UAA	LAC vs LAA	UAC vs LAC	UAA vs LAA
P1 (100, H)	0.21 (0.02)	0.18 (0.00)	0.18 (0.00)	0.17 (0.00)	.3519	.6195	.4057	.6918
P2 (100, V)	0.15 (0.01)	0.15 (0.01)	0.18 (0.05)	0.18 (0.07)	.3391	.3210	.8555	.8845
P3 (200, H)	0.32 (0.06)	0.32 (0.05)	0.25 (0.00)	0.24 (0.01)	**.0142***	**.0043***	.9476	.7097
P4 (200, V)	0.22 (0.00)	0.21 (0.01)	0.20 (0.00)	0.24 (0.00)	.5962	.3067	.7723	.2079

[a] H indicates horizontal; LAA, lower arch aligned; LAC, lower arch crowded; UAA, upper arch aligned; UAC, upper arch crowded; V, vertical (80°).
* $P < .05$, paired *t*-tests.
Asterisks and bold font indicate statistically significant differences.

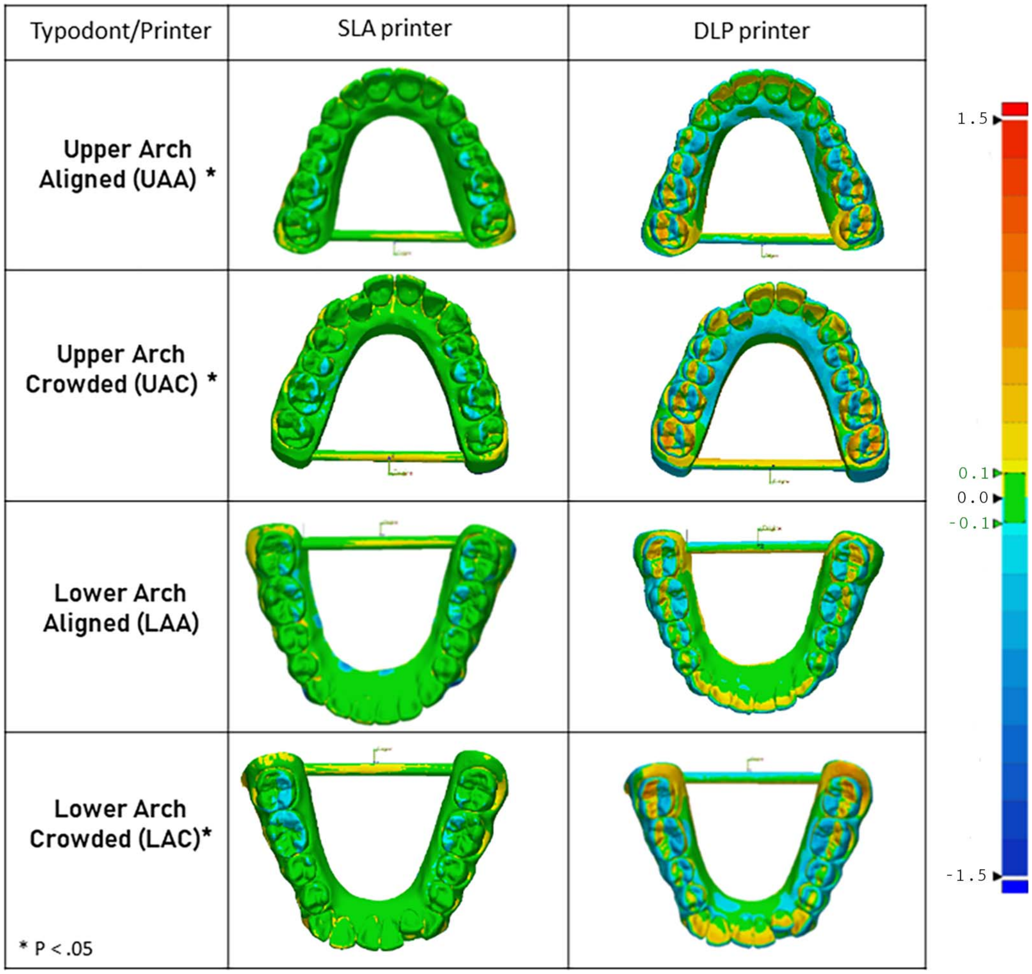

Figure 3. Color map showing the discrepancy between the tested models and the reference master files printed horizontally using SLA and DLP technology. The yellow through red color code indicates areas of expansion, whereas blue indicates areas of contraction. Statistically significant differences (*$P < .05$) in root mean square values (RMS) were found for the upper arch aligned (UAA), upper arch crowded (UAC), and lower arch crowded (LAC) typodonts. Areas in green indicate surface matching within the predefined tolerance limit ($\pm$0.1 mm).

possible to build on prior research to potentially optimize orthodontic digital workflow.

Literature is scarce regarding 3D printing of dental models at higher Z-layers (>100 μm). Therefore, direct comparison of the current study results with others is difficult due to the different values of layer thickness. The fact that the mean RMS values of vertically oriented prints did not differ significantly between SLA and DLP technology (Table 6) is interesting as this suggests that the trueness of dental models printed in a vertical orientation at layer thicknesses between 100 μm to 300 μm may not be affected by the printing technology. On the other hand, DLP-printed crowded models had significantly higher RMS values than SLA when printed horizontally (Table 6), thus suggesting that the vertical orientation should be preferred to the parallel orientation in the DLP system when printing with increased layer heights. This finding was in agreement with Unkovskiy et al.,[10] in which the authors observed that denture bases printed perpendicular to the building plate provided more accurate prototypes for both DLP and SLA systems, which ultimately led to better tissue adaptation. On the other hand, this finding was contradicted by the observations of Rubayo et al.,[4] who found that SLA printing of surgical templates built at an angle of 90° had statistically significant higher RMS values than all other groups did. A possible explanation may lie in the fact that surgical templates have significantly fewer layers and overall printing volume. Hence, it is possible that the similarities in the thickness and shape of printed denture bases and printed orthodontic models influence the ideal printing orientation. Therefore, based on the present data and previously published results, it can be tentatively posited that vertical printing orientations may be better suited for printing high-volume end products at lower resolutions.

With regard to tooth alignment, the SLA-printed crowded models in this study tended to show lower

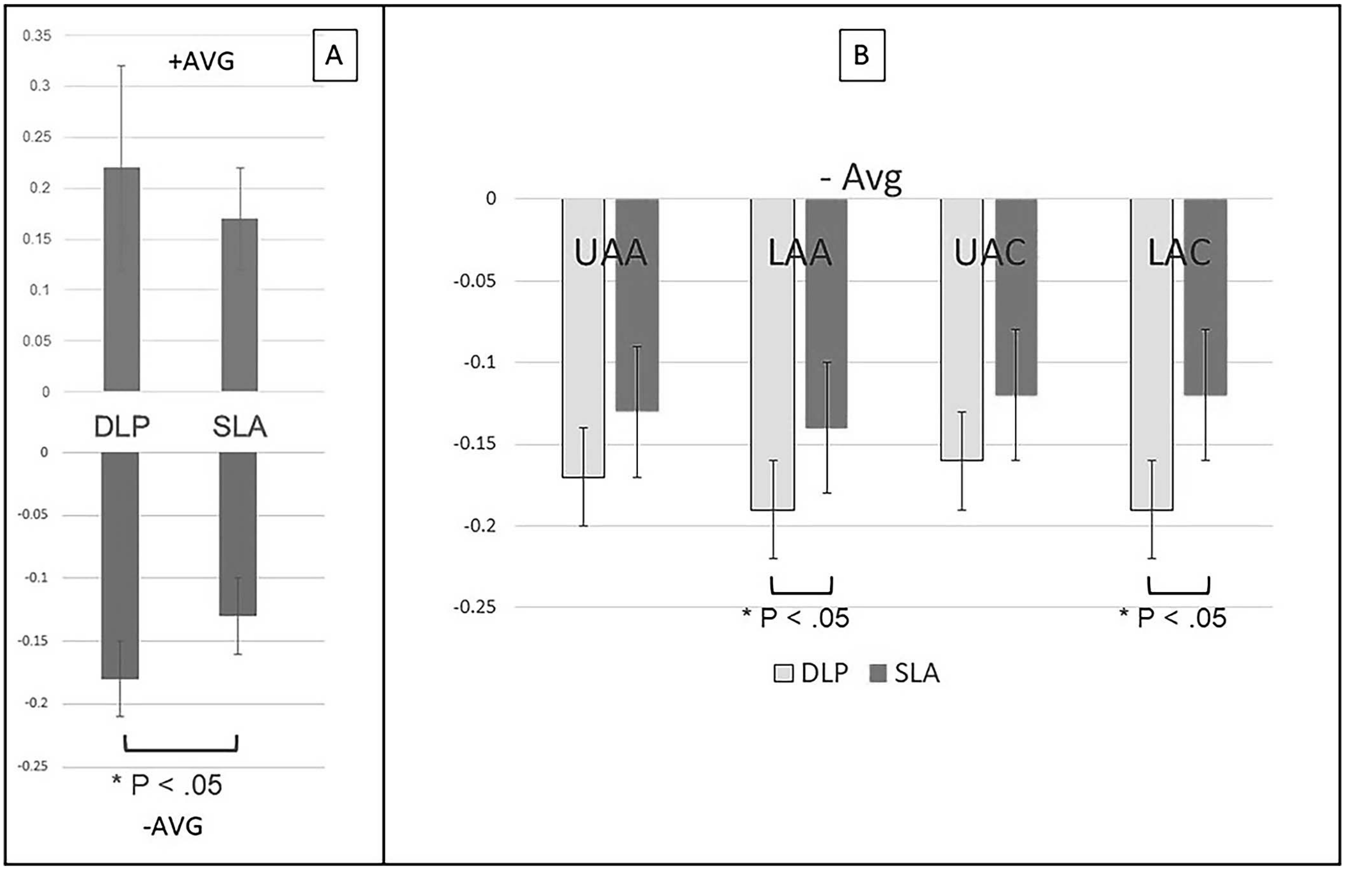

Figure 4. Bar charts illustrating the measure of fit of thermoformed appliances. (A) The vertical axis (in millimeters) represents the mean of all the calculated positive (+Avg) and negative (−Avg) gap distances between the intaglio surface of the appliances and the respective digital models. (B) −Avg differences (in millimeters) between the DLP and SLA appliances in the upper arch aligned (UAA), upper arch crowded (UAC), lower arch crowded (LAC), and lower arch aligned (LAA) typodonts. An asterisk denotes a statistically significant difference ($P < .05$).

RMS values and better trueness than aligned models did, especially when printed at the lowest resolution of 300 μm (Table 4). The opposite was found in the DLP printer, where crowded models showed significantly higher RMS values in both upper and lower arches when printed horizontally at the lowest resolution of 200 μm (Table 5). These findings suggested that the SLA system seems to perform better in crowded dentitions, whereas the DLP system obtained better trueness in aligned dentitions when printing with increased layer thicknesses (100 μm or above). In the comparison of the overall trueness associated with printing systems, the DLP models tended to show significantly higher RMS values than SLA models did when printed horizontally (Table 6). This finding seems to be not only statistically relevant but also clinically meaningful for two reasons. First, the intaglio scans of the TAs fabricated on top of these DLP-printed models showed significantly larger areas of contraction (Figure 4). Second, further analysis of the data revealed that most appliances that showed below average ratings (>3) among orthodontists were fabricated over DLP-printed crowded models with a Z-

Table 6. Mean (SD) Root Mean Square (RMS) Values for the Comparison Between Stereolithography (SLA) and Digital Light Processing (DLP) Printing Systems[a]

System	Orientation	Measure	UAC	LAC	UAA	LAA	UAC	LAC	UAA	LAA
DLP	H	RMS	0.26 (0.08)	0.25 (0.08)	0.21 (0.04)	0.20 (0.04)	**.0000***	**.0014***	**.0470***	.6571
SLA	H	RMS	0.11 (0.02)	0.15 (0.02)	0.15 (0.04)	0.22 (0.06)				
DLP	V	RMS	0.19 (0.04)	0.18 (0.04)	0.19 (0.03)	0.21 (0.06)	.1605	.5813	.2233	.6162
SLA	V	RMS	0.14 (0.02)	0.16 (0.06)	0.15 (0.05)	0.22 (0.12)				

[a] H indicates horizontal; LAA, lower arch aligned; LAC, lower arch crowded; SD, standard deviation; UAA, upper arch aligned; UAC, upper arch crowded; V, vertical (80°).

* $P < .05$, paired *t*-tests.

Asterisks and bold fonts indicate statistically significant differences.

Table 7. Mean Rating Scores (SD) From Three Examiners on a Scale of 1–4 for Quality Control Criteria for Thermoformed Appliances (1 = *Excellent*, 4 = *Poor*)[a]

Quality Control	Retention	Stability	Plastic on Posterior	Plastic on Anterior	Overall
Printing system					
SLA	1.19 (0.32)	1.12 (0.21)	1.02 (0.08)	1.17 (0.24)	1.29 (0.32)
DLP	1.85 (1.12)	1.96 (1.33)	1.12 (0.17)	2.04 (1.29)	1.92 (1.18)
P value	**.0291***	**.0205***	**.0335***	**.0126***	.051

[a] DLP indicates digital light processing; SLA, stereolithography. Refer to Table 1 for additional details on the varying printing parameters in the SLA and DLP printers.

* $P < .05$, paired *t*-test.

Asterisks and bold fonts indicate statistically significant differences.

layer height of 200 μm, thus making this print setting the least reliable according to the data from this study.

Consistent with findings previously documented in the literature,[4] the DLP printer displayed consistently faster printing times when models were printed horizontally. When printed vertically, however, the SLA printer outperformed the DLP printer in speed. This can be attributed to the fact that the printing speed is directly proportional to the Z-layer height. Increasing the layer thickness to 300 μm in the vertical orientation helped speed up the printing process in the SLA system to the point that it became faster than the DLP system printing at 200 μm (Table 2). By the time this study was conducted, it was not possible to identify a DLP commercial resin that would support a print resolution of 300 μm according to the manufacturer's instructions; therefore, this layer thickness was not tested in the DLP printer.

The main limitation of this study was that the TAs were not positioned in the mouths of subjects but instead were tested under laboratory conditions by fitting them on typodonts. Although this method provided clinicians with better visualization for the intimacy of fit, future clinical studies are needed to evaluate the clinical performance of TAs fabricated on top of dental casts printed with thicker layers. In addition, the results of this study may have been affected by the equipment and/or materials used to fabricate the appliances. Despite the limitations, this study represents an important first step in the optimization of 3D-printing parameters for orthodontic applications.

CONCLUSIONS

- Dental casts printed with thicker layers seem to produce accurate working models for orthodontic applications.
- In relation to the parameters tested in this study, the most reliable were
  - SLA: 160 μm and 300 μm
  - DLP: 100 μm
- RMS values showed no significant differences between SLA and DLP systems in the vertical orientation. SLA showed better trueness than DLP when models were printed horizontally.
- The SLA system performed better than the DLP system did in crowded dentitions.
- A Z-layer of 200 μm in the DLP system showed less consistent results, especially for crowded models printed in the horizontal direction. Thus, the vertical orientation should be preferred in the DLP system when printing with increased layer thicknesses.

ACKNOWLEDGMENT

This study was funded by the American Association of Orthodontists Foundation.

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