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A Comparison of Three-Dimensional Printing Technologies on the Precision, Trueness, and Accuracy of Printed Retainers

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A Comparison of Three-Dimensional Printing Technologies on the Precision, Trueness, and Accuracy of Printed Retainers

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Dentistry at Virginia Commonwealth University.

By

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Abstract

A COMPARISON OF THREE-DIMENSIONAL PRINTING TECHNOLOGIES ON THE PRECISION, TRUENESS, AND ACCURACY OF PRINTED RETAINERS

By: Owais Naeem, DDS

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Purpose: The aim of this study was to evaluate the differences in the precision, trueness, and accuracy of 3D printed orthodontic clear retainers produced using printer systems with various printing technologies.

Methods: Retainers (n=15) were printed using four different 3D printers: a stereolithography (SLA) printer, two different digital light processing (DLP and cDLP) printers, and a polyjet photopolymer (PPP) printer. The 3D printed retainers were transformed into a digital file through a cone-beam computed tomography scan that was compared to the original image using a 3D superimposition analysis software. At previously chosen landmarks (R6, L6, R3, L3, R1, L1) retainers were compared to the reference model. The intercanine and the intermolar width measurements were also analyzed for deviations between the samples and the original file. A discrepancy up to 0.25mm was considered clinically acceptable. Precision of printers was evaluated on 5 randomly chosen samples. Trueness was determined by comparing the measurements on printed retainers to those on the original image file. Root mean square (RMS) and percent of points within the tolerance level (inTOL) were also calculated with respect to precision and trueness for each retainer. Samples were analyzed for intra-printer reliability (precision), and inter-printer trueness. Statistical significance was set at $P<0.05$.

Results: Interrater correlation coefficient indicated good agreement and all measurements were within 0.10mm at least 95% of the time. Statistically significant differences were found between printer types among each of the 6 landmarks and the arch widths. When evaluating inTOL and RMS, statistically significant differences in both median precision and trueness among each printer type were found. SLA and PPP printing technologies exhibited both excellent precision and trueness.

Conclusion: Retainers fabricated by SLA, DLP, cDLP, and PPP technologies were shown to be clinically acceptable and accurate compared to the standard reference file. SLA and PPP printers showed greater accuracy, and the DLP and cDLP printers exhibited greater precision. The PPP printer had the most accurate intra-arch measurements followed by the SLA printer, and therefore, based on their high trueness and precision values, were deemed to be the most accurate overall.

Introduction

Recent advances in dental technology have allowed dentists to use intraoral scanners to create digital models for diagnosis and treatment planning. One particular advancement in digital dentistry has been the introduction of three-dimensional (3D) printing where digital models are used to fabricate patient models, appliances, and surgical guides.[1]

Digital models offer several advantages over physical plaster models, including increased comfort, less storage space, and ease of access.[2–4] Previous studies on the accuracy of the 3D printed models have shown that intra-arch and inter-arch relationships are accurately represented;[2,5–8] therefore, it is anticipated that they will completely replace the traditional plaster casts in the near future.[1]

3D printing is a process of fabricating three-dimensional structures by joining material on a layer-by-layer basis using a 3D digital file.[9] Similar to a standard two-dimensional printer, a 3D printer adds the z-axis introducing a vertical height. A "build layer" is the unit for each layer of material in microns that is laid down and stacked up by the printer.[1] Digital models of dental arches can be printed using a 3D printer without distortion in shape.

Thermoformed clear retainers are widely used for retention after the completion of orthodontic treatment. Currently, thermoplastic appliances such as aligners and clear retainers are fabricated on physical models previously printed with 3D printers. The conventional process of obtaining a dental impression, creating a plaster model, and then thermoforming a biocompatible plastic sheet is not only an inefficient and costly procedure, but also patient unfriendly. However, with the use of digital technology and 3D modeling, potential procedural errors can be avoided. For example, alginate and polyvinyl siloxane (PVS) impressions are prone to pulls, tears, bubbles, voids distortion, sensitivity to temperature, technique, time, chemistry, shrinkage and model pouring discrepancies.[10] If a clear retainer can be accurately 3D printed directly from a digital scan, then extra steps of taking an alginate or PVS impression and thermoforming the plastic sheet on the cast can be eliminated. Furthermore, 3D printing may help to improve the cost efficiency and patient comfort.

In the literature, the first attempt to fabricate a 3D printed retainer was made by Nasef et al[11] in 2014 where the appliance was built with the selective laser sintering technique directly from a cone beam computed tomography (CBCT) scan. In 2017, the same authors compared the accuracy of 3D printed retainers to vacuum-formed traditional retainers, and reported no significant differences in the linear relationships between the two groups. The measurements were carried out with digital calipers.[12]

In 2019, Cole et al.[13] also studied the accuracy and precision of digitally printed retainers by comparing them to traditional vacuum formed retainers. The investigators performed the linear measurements on predetermined reference points by superimposing the original digital image with the digital image of the 3D printed retainer. In that study, the analyses were conducted using a computer software to eliminate the operational errors. The authors concluded that the differences between the two groups were small enough to be considered insignificant based on the assumption that deviations up to 0.5mm are considered clinically acceptable based on the American Board of Orthodontics' increments for grading plaster models.[14] This value, however, is different from a study by Johal et al.[15], in which the fit of thermoformed retainers was tested under laboratory conditions, and a discrepancy of up to 0.25mm was used as a threshold for a clinically acceptable fit. The 0.25mm value was chosen as maximum allowed difference in the measurements between the retainer and the reference model bases on a previous study by Boyd and Waskalic.[16]

Finally, a recent study by Jindal et al.[17], looked at the mechanical properties of aligners printed on a stereolithography (SLA) printer compared to the retainers fabricated by thermoforming. The study showed that 3D printed aligners were geometrically more accurate and resistant to the load with low displacement as compared to thermoformed appliances. It was also argued that 3D printed aligners were more resistant to the average human biting force than thermoformed aligners are to these forces.

Currently, there are several 3D printing systems available in digital dentistry. One of the most established technologies, SLA, consists of a photosensitive resin, a platform for building the object, and an ultraviolet laser to cure the resin on the platform (Figure 1a). In this additive manufacturing process, the laser light cures each layer, and as the layer is cured, the tray descends to add more uncured resin until a shape is formed. Digital light processing (DLP) is another 3D printing system used to create an object (Figure 1b). A DLP printer operates in the same way as an SLA printer, but in contrast, a projector instead of a laser, cures the entire layer each time. Since the laser of an SLA printer draws out the object in each layer rather than stamping out each layer, an SLA printer is believed to be a slower printer than a DLP printer.[1] Another variation of the DLP printer is a continuous digital light processing (cDLP) printer. This is a newer approach where the build plate moves constantly in a vertical direction allowing light to cure the polymers without interruption. Finally, a polyjet photopolymer (PPP) printer operates similarly to a standard inkjet printer, except it also has a vertical component where a laser cures the resin as the material is jetted out by nozzles (Figure 1c). This printer allows for the smallest microns of build layers which can lead to a better quality of print.[1] PPP printers are limited to a slice thickness of 16μm and 32 μm. The different types of printers vary in the resin material used, the print layer heights, and the curing modalities. To date, there is limited information on the 3D printing technology to direct clinicians toward the most accurate and precise printer to use in their practices.

Previous research comparing different printing technologies has shown that 3D printed models are accurate and precise. However, one study by Kim et al.[18] on the precision and trueness of dental models printed using the SLA, DLP, and PPP technologies reported significant differences in dental and occlusal measurement data. The PPP and DLP printers were found to be more precise than the SLA systems with the PPP printers showing the highest accuracy. Also, in previous investigations, the accuracy of printing dental models was evaluated manually with digital calipers instead of using a more reliable method such as a 3D analysis software.[19,20]

In summary, while previous research focused on the accuracy of printed models, there is limited information on the accuracy and precision of 3D printed retainers fabricated directly from a digital scan. The purpose of this study was to evaluate the precision, trueness, and accuracy of clear retainers produced directly from a standard digital file using 3D printers with different technologies. The null hypothesis was that there are no significant differences in the precision, trueness, and accuracy of retainers fabricated using different 3D printing technologies.

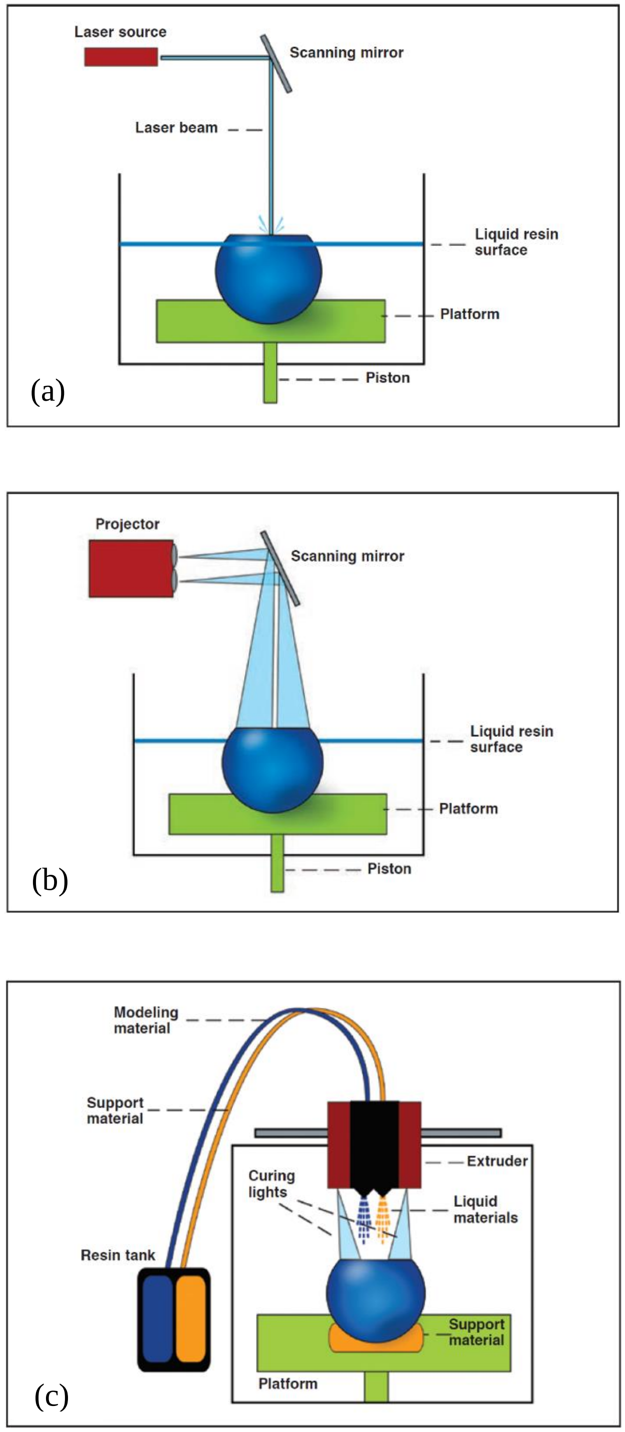


Figure 1. Schematic drawings showing the technology used for (a) stereolithography (b) digital light processing and (c) polyjet printers. From "Three-dimensional printing technology," by C. Groth, N.D Kravitz, P. E Jones, J. W. Graham, W. R. Redmond. *J. Clin. Orthod. 2014;48(8):475–85.* Reprinted with permission.

Methods

In this study, a previously created standard tessellation language (STL) file of a retainer was used to fabricate the samples.[13] The digital image of the retainer was altered by placing markers with Autodesk Meshmixer**TM** software (Autodesk, Inc., San Rafael, California) (Figure 2). These reference points, 1.5mm in diameter were digitally placed on the mesiobuccal cusps of the first molars (R6, L6), the cusp tips of the canines (R3, L3) , and the middle of the incisal edges of the central incisors (R1, L1). These landmarks helped to eliminate error during the superimposition step later in the study. At this time, the digital model was saved as an "STL" file for the fabrication of 3D printed retainers using four types of printers.

Figure 2. Standard STL file with the reference points on the mesiobuccal cusps of the first molars, the cusp tips of the canines, and the middle of the incisal edges of the central incisors

To fabricate clear retainers, the following 3D printers were used: An SLA printer (Form 3, Formlabs Inc.; Somerville, MA), a DLP printer (MoonRay, SprintRay Inc.; Los Angeles, CA), a cDLP printer (Envision One cDLM Dental, EnvisionTEC, Dearborn, MI), and a PPP printer (Objet Eden260VS, Stratasys, Eden Prairie, MN). These systems were chosen to represent the leading technologies currently available in digital dentistry.

The same STL file was used to print a total of 60 retainers (n=15, each for 4 printers) with the resin specific to each system based on the manufacturer's recommendation via private communication. The following resins were used: Formlabs Dental LT Clear Resin (Formlabs Inc.; Somerville, MA) for the Form 3, SprintRay Splint Resin (SprintRay Inc.; Los Angeles, CA) for the MoonRay DLP, E-Guard (EnvisionTEC, Dearborn, MI) for the EnvisionTEC cDLP, and VeroClear (Stratasys, Eden Prairie, MN) for the Objet Eden260VS. Retainers in the PPP group were printed flat, while the appliances in the other printer groups were printed at an angulation according to the individual printer setup. Retainers in the SLA, DLP, and cDLP groups were printed at 100µm due to resin limitations while the PPP was limited to 16µm for layer thickness. Following the printing process, each retainer was subjected to the individual post-printing cleaning process as described by the manufacturer (Figure 3).

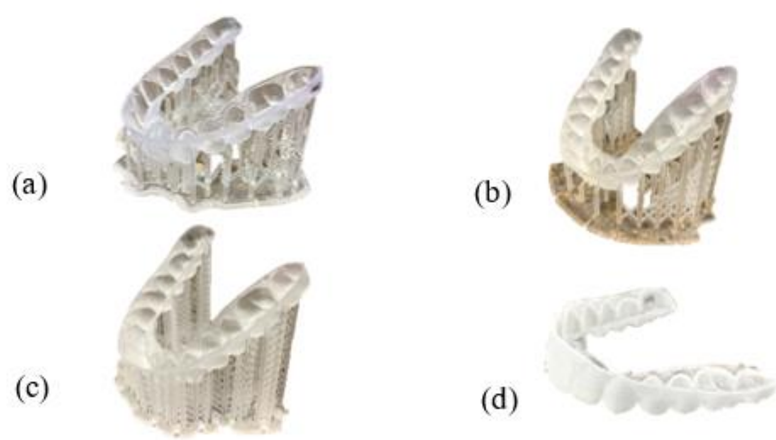


Figure 3. Post-processed printed retainers with (a) Stereolithography, (b) Digital light processing, (c) Continuous digital light processing, and (d) Polyjet photopolymer technology

A pilot study has determined that the digital image of printed retainers was more accurate when created with CBCT instead of intraoral scanner. The improved accuracy with the use of CBCT was attributed to the elimination of a scanning spray layer necessary when using an intraoral scanner to produce the digital image. Therefore, the printed retainers that were post-cured without the removal of any additional supports were scanned using CBCT to create their corresponding STL files.

The digital images were then superimposed using a best-fit method on a 3D analysis software (Geomagic Control; 3D Systems, Rock Hill, SC) comparing the digital images of the printed retainers (experimental) to the digital image of the reference retainer (control) A total of 6 previously chosen reference points (R6, L6, R3, L3, R1, L1) were utilized to evaluate the accuracy of the pairings (Figure 4). In addition, intercanine width (ICW) and intermolar width (IMW) calculations were also performed to make comparisons between the digital reference retainer and the experimental group samples (Figure 5).

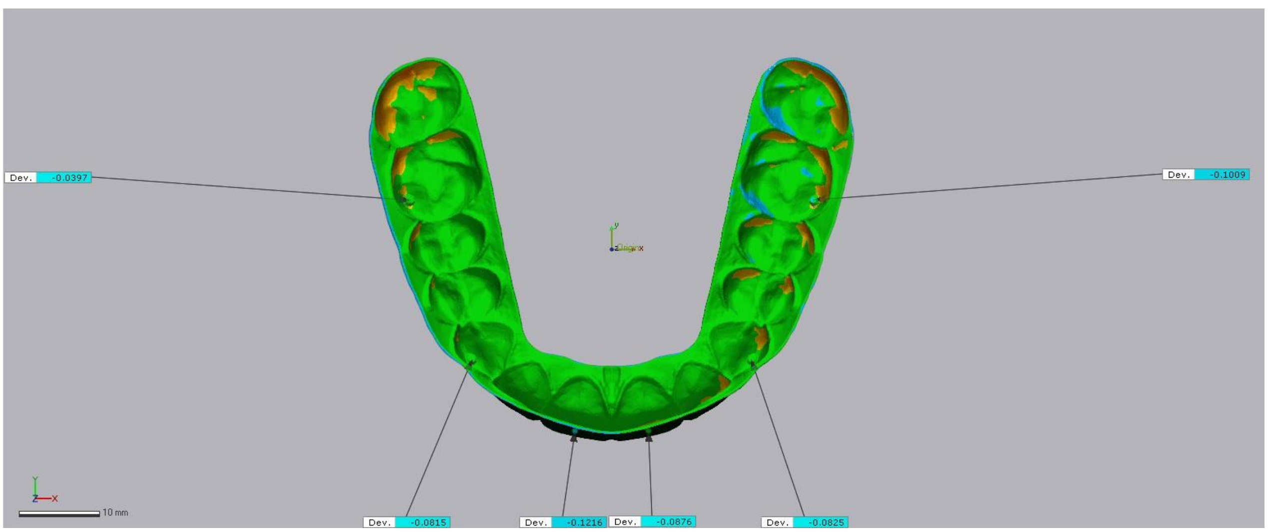


Figure 4. DLP superimposition to reference STL file with reference points

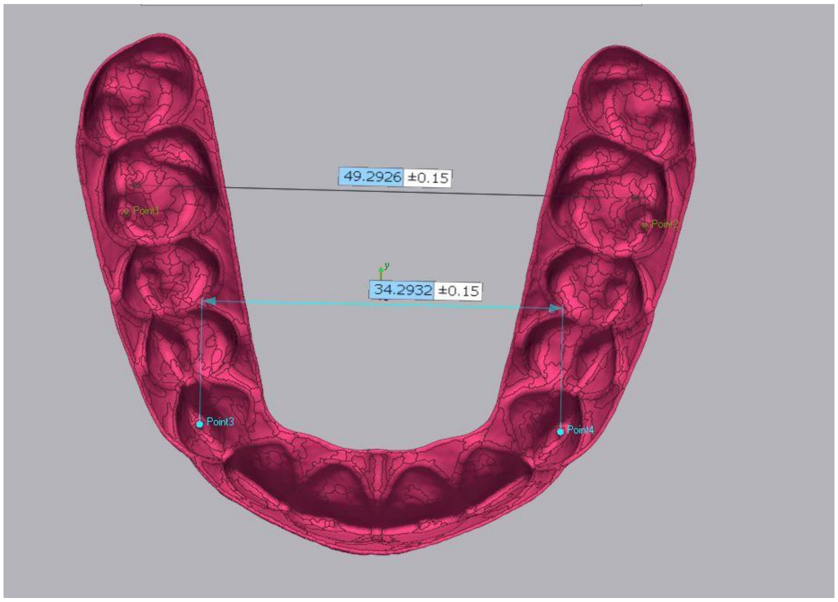


Figure 5. Intercanine and intermolar width calculations

Trueness, or the closeness of the printed retainer to its true model, was determined by comparing the digital data of the printed retainer to the reference STL file (Figure 6). To determine precision, 5 of the 15 printed retainers were randomly chosen for each printer and comparisons were made. These combinations included retainers 1:2, 1:3, 1:4, 1:5, 2:3, 2:4, 2:5, 3:4, 3:5, 4:5 resulting in a total of 10 comparisons per printer group. Using the 3D analysis software, root mean square error (RMS) values and the percent of points within the tolerance level (inTOL) were calculated (Figure 7). Root mean square was determined by the formula

$RMS = \sqrt{\frac{\sum_{i=1}^{n}(x_{ref} - x_i)^2}{n}}$ where x_{ref} is the measurement of the reference model, x_i is the measurement of the test model being compared, and n is the total number of measurements. Precision and trueness of the retainers were then assessed where a low RMS value and a high inTOL percentage indicated a good fit. Finally, accuracy representing the combination of both precision and trueness was determined.

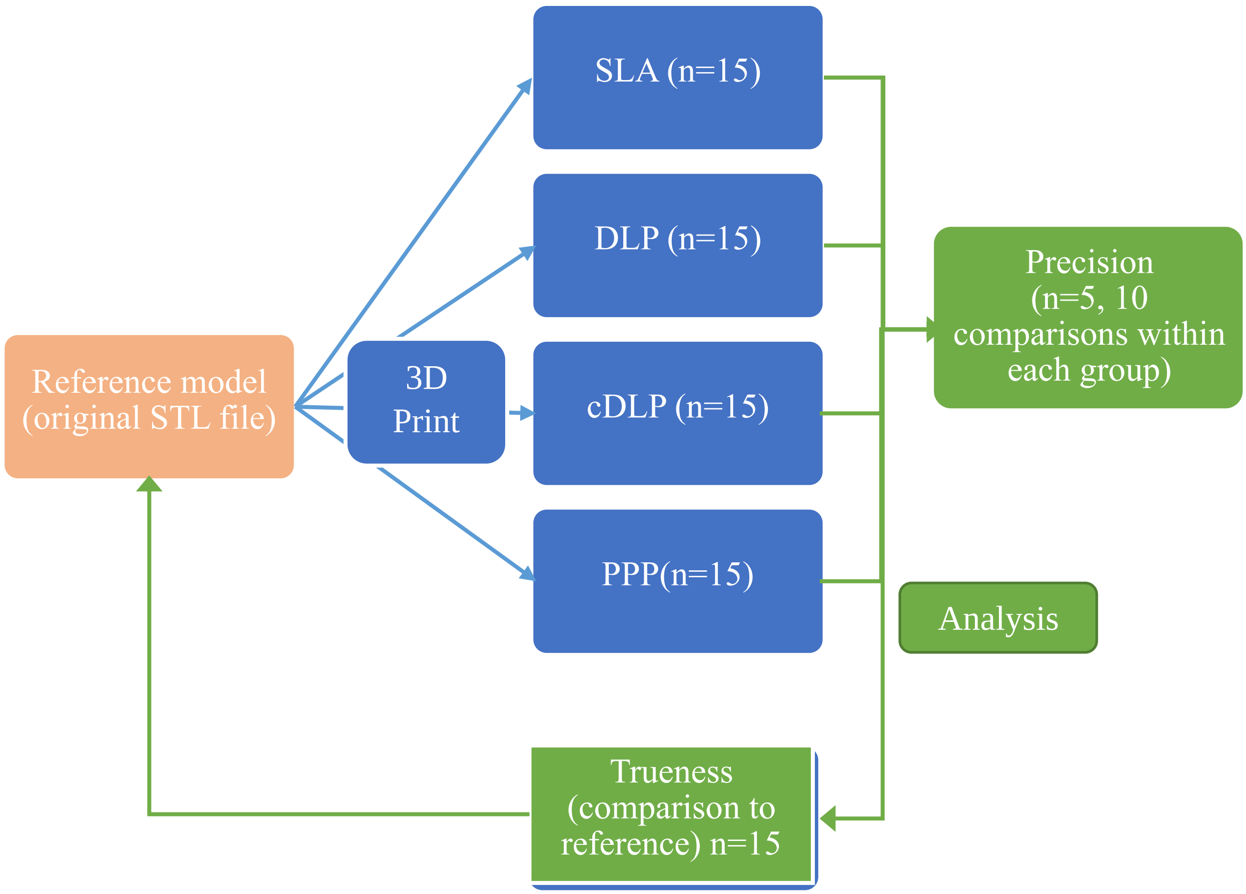
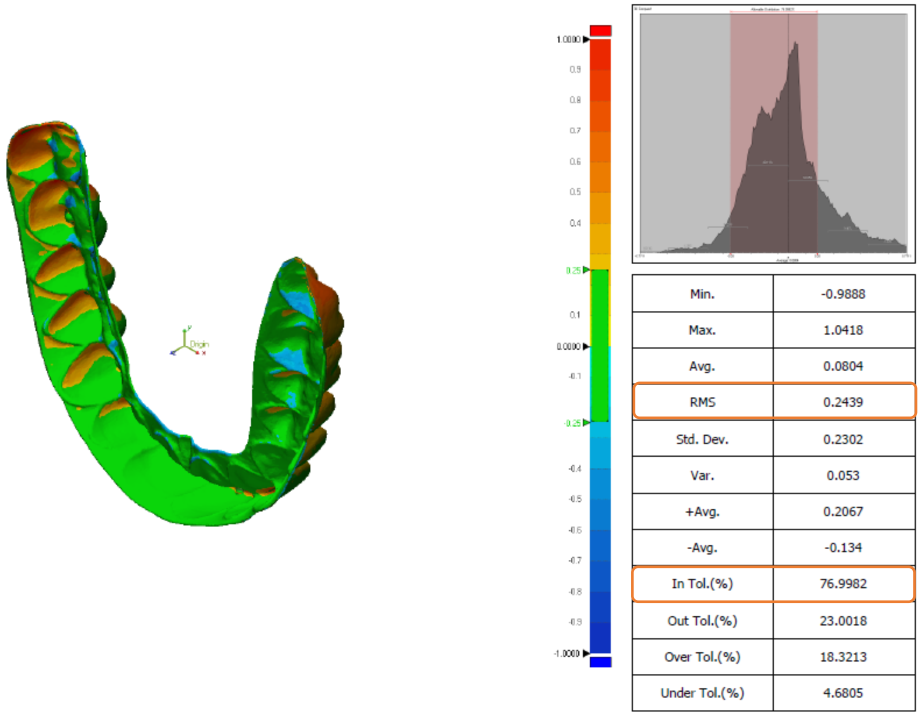


Figure 6. Outline for design of printing process. 60 retainers were printed (n=15, each). 5 randomly selected retainers from each printer were compared to each other for a total of 10 combinations for precision and 15 retainers were compared to the reference for trueness.



Min.	-0.9888
Max.	1.0418
Avg.	0.0804
RMS	0.2439
Std. Dev.	0.2302
Var.	0.053
+Avg.	0.2067
-Avg.	-0.134
In Tol.(%)	76.9982
Out Tol.(%)	23.0018
Over Tol.(%)	18.3213
Under Tol.(%)	4.6805

Figure 7. The DLP retainer to reference STL superimposition analysis output with RMS (mm) and inTOL (%)

STATISTICAL ANALYSES

Interrater correlation coefficient (ICC) was used to determine the agreement between two raters for the ICW and IMW assessments as well as measurements at the six landmarks. Analysis of variance (ANOVA) was used to test for differences in accuracy at each of the six designated reference points based on the type of printer and post-hoc pairwise comparisons were adjusted using Tukey Honestly Significant Difference Tests. Two-way student t-tests were used to evaluate if the mean distance of the canine and molar measurements from the printed retainers was different from the calculated distance of the original STL file. Additional ANOVA models were used to assess precision and trueness between printer types based on RMS values. Estimated means and 95% confidence intervals were reported. Due to non-normality of the RMS data, nonparametric Kruskal-Wallis tests were used to assess precision and trueness between printer types for percent within the defined tolerance (+/- 0.25). Post-hoc pairwise comparisons were adjusted using Dunn’s multiple comparison tests. Median values and bootstrap 95% confidence intervals using 10,000 samples were reported. All statistical analyses were performed in R (version 3.6.1, R Development Core Team; University of Auckland, New Zealand). All statistical tests were assessed at the 0.05 alpha level of significance.

Results

A total of 15 retainers were printed for each of the four types of printing technologies including SLA, DLP, cDLP, and PPP. For each printer, two raters were asked to assess the spatial difference between the digital image of the printed retainer and the original STL file at the six previously determined landmarks: R6, L6, R3, L3, R1, and L1. In addition, the intercanine and intermolar widths were also measured to make comparisons between the printed retainers and the original STL file.

Interrater correlation coefficient indicated good agreement between two raters for all but the L6 landmark (Table 1). The differences in the measurement values between the two raters were so small that the agreement was also reported as the percent agreement within 0.10mm (Table 1). At all landmarks, measurements were within 0.10mm at least 95% of the time indicating clinical insignificance. Therefore, measurements from only one rater were used for further analyses.

Table 1. Intraclass Correlation Coefficients between the two raters for each landmark.

Landmarks	ICC (95% CI)	Percentage with <0.10mm difference	P-Value
R6	0.876 (0.801, 0.924)	100%	<0.0001
L6	0.701 (0.544, 0.810)	98.3%	<0.0001
R3	0.894 (0.814, 0.938)	98.3%	<0.0001
L3	0.933 (0.882, 0.961)	100%	<0.0001
R1	0.804 (0.693, 0.878)	96.7%	<0.0001
L1	0.749 (0.614, 0.842)	95%	<0.0001
ICW	0.990 (0.984, 0.994)	98.3%	<0.0001
IMW	1.000 (1.000, 1.000)	100%	<0.0001

The printing accuracy was evaluated across printer types using one way ANOVA. The landmarks were used to evaluate the accuracy of the printed retainers compared to the original STL file. A lower estimated mean discrepancy indicated a closer fit for each given landmark. Statistically significant differences were found between printer types among each of the 6 landmarks. The intercanine and intermolar width measurements also indicated differences in accuracy between the printers (Table 2). There was a significant variation within the printers for the least mean difference at the molar, canine, and incisor landmarks, with the PPP printer showing the lower mean difference in the incisors (R1, L1), the DLP printer showing lower mean difference in the canines (R3, L3), and the cDLP and SLA printers exhibiting lower mean differences in the molars (R6, L6). The estimated mean difference for each printer type at each landmark fell within the 0.25mm tolerance level (Figure 7).

Table 2. Post-hoc Tukey HSD tests showing the estimated mean discrepancy between digital image of the printed retainers and the original STL image for each measurement, across each printer. P-values correspond to the overall one-way ANOVA tests. The printers with the same letter indicate that they are not significantly different from each other.

Landmark	Printer Type	Estimated Mean Discrepancy (mm)	Standard Error	P-Value
R6				<0.0001
	SLA	0.075	0.013	a
	DLP	0.149	0.013	b
	cDLP	0.075	0.013	a
	PPP	0.148	0.013	b
L6				<0.0001
	SLA	0.089	0.011	ab
	DLP	0.102	0.011	b
	cDLP	0.047	0.011	a
	PPP	0.149	0.011	c
R3				0.0083
	SLA	0.095	0.018	ab
	DLP	0.045	0.018	a
	cDLP	0.095	0.018	ab
	PPP	0.138	0.018	b
L3				<0.0001
	SLA	0.110	0.011	b
	DLP	0.043	0.011	a
	cDLP	0.129	0.011	b
	PPP	0.093	0.011	b
R1				0.0056
	SLA	0.098	0.019	ab
	DLP	0.165	0.019	b
	cDLP	0.156	0.019	b
	PPP	0.081	0.019	a
L1				0.0007
	SLA	0.110	0.015	ab
	DLP	0.128	0.015	b
	cDLP	0.153	0.015	b
	PPP	0.060	0.015	a
ICW				<0.0001
	SLA	0.314	0.030	a
	DLP	0.642	0.030	c
	cDLP	0.469	0.030	b
	PPP	0.262	0.030	a
IMW				<0.0001
	SLA	0.588	0.057	b
	DLP	1.108	0.057	c
	cDLP	0.997	0.057	c
	PPP	0.145	0.057	a

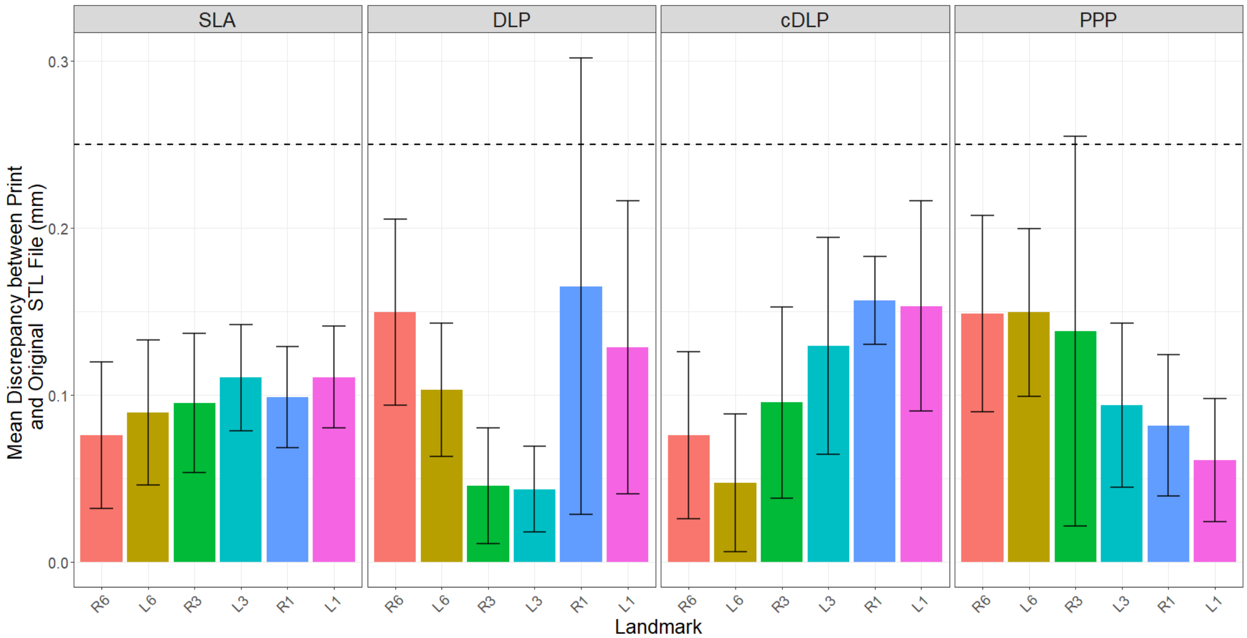


Figure 8. Bar plots illustrating the mean difference in print accuracy for each landmark, across each print type. The error bars represent one standard deviation away from the mean difference. The dashed line represents the 0.25mm difference.

As shown in Table 2, the PPP printer featured much lower mean differences for the ICW and IMW measurements. A two-way Student t-test was completed to compare the mean distance in millimeters across the canine and molar points of the printed retainers to the original STL file. The retainers in the PPP printer group exhibited a close replication of the original STL model with an ICW value of 34.54mm versus 34.80mm for the reference model. Similarly, the samples in this printer group also had an IMW measurement (50.10mm) that was very close to the original value for the reference model (IMW=51.15mm). This was followed closely by the SLA printer with 34.48mm and 49.57mm for ICW and IMW, respectively. All measurements were significantly different except the IMW of the PPP printer (P=0.2333), indicating no significant difference between the average mean distance of this printed retainer compared to the original STL file at the molars.

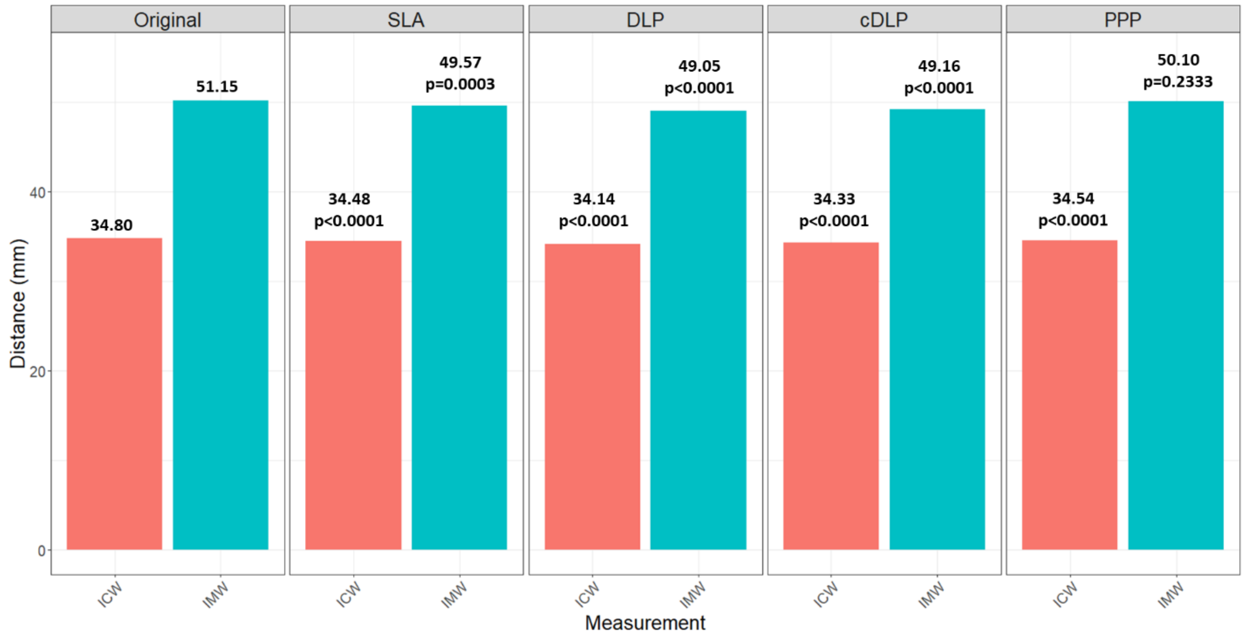


Figure 9. Bar plots illustrating how the mean distance (mm) across canine and molar points compares to the original STL file for each type of printer. P-values are from two-way Student t-tests assessing if the mean distance is different from 34.80mm and 51.15mmfor ICW and IMW, respectively.

When evaluating the percent of points within the tolerance level (inTOL), statistically significant differences in both median precision and trueness among each printer type were found (Table 3A). For precision, the cDLP samples were found to have the highest precision with a median of 99.9% of points within the preset tolerance (bootstrap CI=99.7, 100.0). However, post-hoc analysis showed that they were not statistically different from the DLP retainers. For trueness, the SLA retainers were found to have the highest trueness with a median of 94.9% of points within the preset tolerance bounds (bootstrap CI=89.4, 99.1), yet they were not statistically different from PPP samples.

Similarly, the RMS data indicated statistically significant differences in the mean precision and trueness values among each printer type (Table 3B). Once again, the cDLP retainers exhibited the highest precision (mean=0.052mm; 95% CI=0.0317, 0.0724) while the SLA samples had the highest trueness (mean=0.121mm; 95% CI=0.102, 0.140). However, in post-hoc analysis, the cDLP retainers were not found to be statistically different from the DLP samples in precision, just as the SLA ones were not found to be statistically different from the PPP retainers in trueness.

Table 3. Evaluation of precision and trueness for both inTOL and RMS across each print type.

(A)	inTOL*(%)				
Measure	SLA	DLP	cDLP	PPP	P-Value
Precision#	97.9 (85.9, 99.8) b	99.4 (98.8, 100.0) ab	99.9 (99.7, 100.0) a	97.6 (92.7, 98.9) b	0.0015
Trueness#	94.9 (89.4, 99.1) b	75.3 (74.0, 76.6) a	82.6 (80.7, 83.9) a	93.3 (88.4, 94.4) b	<0.0001
(B)	RMS**(mm)				
Measure	SLA	DLP	cDLP	PPP	P-Value
Precision##	0.111 (0.0905, 0.1312) c	0.067 (0.0467, 0.0873) ab	0.052 (0.0317, 0.0724) a	0.101 (0.0804, 0.1210) bc	0.0005
Trueness##	0.121 (0.102, 0.140) a	0.242 (0.223, 0.261) c	0.203 (0.184, 0.221) b	0.151 (0.132, 0.170) a	<0.0001

* Kruskal-Wallis test with post-hoc Dunn’s multiple comparison tests
# Median (95% bootstrap confidence interval using 10,000 samples)
** ANOVA with post-hoc Tukey’s multiple comparison tests
Mean (95% confidence interval)

Discussion

As the world of 3D digital manufacturing has advanced, orthodontics has embraced these changes wholeheartedly. With the advent of intraoral scanning, treatment planning and record-keeping have moved into the digital realm, increasing patient comfort while decreasing storage space needed for the practitioner.[3,4] Researchers have shown that these digital scans can be paired with a 3D printer to directly create retainers and clear aligners.[11,13,17] Traditionally, these clear appliances were fabricated using thermoforming plastics on either a plaster model or a 3D printed model. The next evolution in this process would be to create an accurate 3D printed retainer directly from a patient's intraoral scan. Previous studies have shown that 3D printed models replicate the occlusion accurately so that they are reliable for diagnosis and treatment planning in orthodontics.[5–8] However, fabricating retainers and clear aligners directly from a digital scan is still very much at its infancy and there is limited information on the accuracy of these appliances. [18–20] This study focused on the accuracy, precision, and trueness of 3D printed retainers fabricated by four different printing technologies.

To evaluate accuracy, previously determined six reference points (R6, L6, R3, L3, R1, and L1) were used for superimposition of the digital image of the printed retainer on the original STL image. This method consisted of measuring the mean differences across these landmarks to evaluate the closeness of the fit of the samples to the control image, similar to Cole et al.[13]

However, in the current study 1.5mm ball markers were placed virtually on the digital images to aid with choosing the landmarks, a method to improve the superimposition procedure used in the study by Cole et al.[13] In addition, using the RMS feature of the Geomagic software, the overall fit error was assessed for the precision and trueness of the printed retainers, similar to the technique used by Kim et al.[18]

The intercanine and intermolar width dimensions on the digital images of the printed retainers were smaller than the values on the standard reference file. The least difference in the measurements (0.262mm and 0.145mm, for the ICW and IMW, respectively) between the printed retainer and the original file was observed in the PPP group followed by the SLA group (0.314mm and 0.588mm for the ICW and IMW, respectively). The retainers in these groups were noted to exhibit high accuracy ($P<0.0001$). However, the measurements of the DLP group (0.642mm and 1.108mm for the ICW and IMW, respectively) and cDLP group (0.469mm and 0.997mm for the ICW and IMW, respectively) exhibited larger deviations from the original file. The samples in these groups were found to be significantly different than the ones in the PPP and SLA groups. Furthermore, when comparing the average distance of the prints in the canine and molar regions with the original STL file, the PPP intermolar width was not significantly different ($P= 0.2333$). The intercanine width of the PPP although significantly different ($P<0.0001$), was the closest in value to the original STL file mean distance. Discrepancies in the intercanine and intermolar width measurements between the retainers and the original file indicate that the resin has experienced dimensional change during the manufacturing process. Shrinkage due to polymerization may have occurred due to the differences in the print angulation possibly allowing for intra-arch distortion to occur. The retainers in the PPP group were printed flat as opposed to the ones in the other printer groups oriented at 30 to 45 degrees of angulation.

Therefore, one possible explanation for less distortion in the PPP group may be attributed to the printing settings of these systems.

Furthermore, the z-axis is printed at a constant layer height based on the micron settings of the printer and resin. The PPP group was printed at the smallest micron setting (16µm) compared to the remaining printers (100µm), and thus had the smallest printing height and the smoothest finish. Although this may seem to indicate better accuracy, previous studies have argued that smaller build height does not lead to greater accuracy due to a greater potential for error.[21] This study proved that increased accuracy was possible regardless of layer thickness as evidenced by the PPP and SLA results.

Based on the study by Boyd and Waskalic,[16] for an aligner to cause tooth movement a minimum of 0.15 to 0.25mm distance needs to exist between the cast and the appliance. Therefore, in this study, differences up to 0.25mm were considered clinically acceptable for retention, and statistical analyses were performed based on this threshold value. The samples in all four printer groups showed mean discrepancies less than 0.25mm at the reference points indicating accuracy within the clinical acceptance tolerance. However, it must be noted that to evaluate whether a printer retainer is accurately reproduced from its digital file, the overall retainer fit is more important than its adaptation at selected landmarks.

Although retainers in all printer groups were deemed accurate and clinically acceptable, there were statistically significant differences between printer types for each landmark. This method showed no consistency between the printers with the cDLP and the SLA retainers showing less error in the molar region, the DLP retainers showing the least error in the canine region, and the PPP and SLA showing the least errors in the incisor region. Why the appliance had a better fit at one landmark versus another may be due to several reasons including print angulation, location of the model on the baseplate, post-processing procedures of the retainers, overexposure of some layers as the build develops due to a clear resin, and finally, errors from the CBCT scan.[22]

Therefore, the overall fit method used in this study to determine precision and trueness was a better approach when evaluating the accuracy of printing technologies. The total percentage of points that were below 0.25mm mean difference shown as a percentage within the tolerance (inTOL) was 99.9% and 99.4% for the cDLP and DLP, respectively. Although these appliances in these groups were found to exhibit excellent precision, when comparing the measurement data to the reference file, the inTOL percentages of cDLP and DLP were only 82.6% and 75.3% respectively, indicating low trueness. Since accuracy is defined as the combination of both the precision and trueness, the cDLP and DLP retainers were less accurate than the SLA and PPP aligners that had high percentages in both precision and trueness. In fact, these aligners were noted to be physically smaller than the reference digital model as evidenced by the discrepancy in the ICW and IMW measurements.

The precision and trueness of the retainers were further evaluated with the interpretation of the RMS data. The SLA and PPP printers had the least precision (RMS, 0.111mm and 0.101mm, respectively) and the highest trueness (0.121mm and 0.151mm, respectively). Retainers in these groups yielded measurement data closer to the true value of the reference model than the appliances in other printer groups, and therefore, the SLA and PPP retainers showed precision, trueness, and accuracy.

RMS allows the offset error to be represented more accurately since the effect of positive and negative values of the difference of measurements of 3D structures is eliminated. As more studies begin to use this method, there will be more accurate comparisons made. In a previous study comparing models fabricated with different printing technologies, the researchers found the PPP printer to have the smallest RMS value for trueness followed by SLA and DLP printers.[18] In our study, SLA printer exhibited a smaller RMS value (0.121mm) followed by PPP (0.151mm) and DLP (0.242mm). However, the SLA and PPP printers were not statistically significantly different.

No study has measured the precision of 3D printed retainers, however, in the Kim et al.[18] study, the PPP showed the highest precision followed by DLP and SLA for 3D models, while in our study, the DLP showed the highest precision, followed by PPP and SLA for 3D retainers. The PPP and SLA printers complete each layer of a print by curing point by point, and while this is more accurate or true in this case, it is prone to greater errors. However, a DLP printer uses a projector to cure the resin layer by layer, allowing for a quicker printing task with less error in repeated prints, therefore creating more precise models.

In this study, four print failures were observed during the printing process. In the cDLP group, three samples exhibited "cupping" at a part of their canine cusp tips. This is a phenomenon that occurs when the model has a lack of support in a certain area leading to a poor surface finish.[23] If these "defective" retainers were to be placed inside a patient's mouth, it is possible for the appliance not to fit well. Several printer software are able to recognize this problem when it occurs and can compensate the shortcomings by correcting the angulation of the model or adding more supports in that area. However, in the current study the cDLP software did not identify and correct this issue. The fourth failure occurred in the PPP printer group where the water jet in post-processing had warped the final retainer causing a change in the shape and thus rendering the physical print useless. Nevertheless, this is an issue that can be easily avoided by careful post-processing.

While this study focused on the overall fit and the accuracy of specific landmarks, certain important landmarks could have been overlooked. While the overall fit for the retainers was clinically acceptable based on the average mean discrepancy in RMS values, there were retainers with discrepancies in certain areas reaching almost 1.0mm, or four times the accepted threshold (Figure 7, the minimum and maximum values.). This was more commonly observed in the DLP and cDLP retainers than in the SLA and PPP appliances. In many instances, these disparities were located at smooth surface areas such as the buccal and lingual of the posterior teeth in red and blue colors on color-coded superimpositions indicating a lack of good fit. On the other hand, the superimposition of an ideal retainer would display a homogenous green color. Therefore, future studies are warranted to analyze the smooth surface regions on the retainers, and the fit of these appliances on these areas.

Further studies on print angulation and post-processing methods can provide information on how to fabricate the most accurate and cost- and time-efficient retainers. Modifications in print angulation can increase the number of retainers printed at one print activity by optimizing the platform area. Adjusting the supports can bring the cost down by conserving the amount of resin used to print.[24] While the cost- and time-efficiency of the printers were not evaluated in this study, these are important factors that would help orthodontists when choosing a printer to purchase. Nevertheless, the ability of a 3D printer to fabricate accurate and precise appliances should remain the driving force in the decision-making process.

Currently, there is no approved commercially available biocompatible resin for fabricating clear orthodontic retainers directly from a digital image file, however in 2018, a new compatible resin material was announced to be in development by EnvisionTEC (EnvisionTEC, Inc; Dearborn, MI) for direct 3D printing of retainers and aligners.[25] This study attempted to elucidate some of the concerns over the current printing technologies available by sharing their individual precision, trueness, and accuracies using the current resins available. Based on the results of this study, all four printers were shown to print clinically acceptable retainers, with PPP and SLA printing the most accurate and DLP and cDLP printing the most precise retainers.

Another limitation of the current study was that the retainers were compared to a digital reference retainer. Future studies comparing the 3D printed retainers to a thermoformed retainer are warranted as currently clear retainers are manually fabricated in the lab using the thermoforming technique. Also, in the future, an approved resin material utilizing these printing modalities will allow orthodontists to evaluate the mechanical and physical properties to better compare thermoformed clear retainers to 3D printed retainers and take the next step in the evolution of orthodontics.

Conclusions

Clear orthodontic retainers fabricated by 3D printing systems with the SLA, DLP, cDLP, and PPP technologies were shown to be clinically acceptable and accurate compared to the standard reference file. While SLA and PPP printers showed greater accuracy, the DLP and cDLP systems exhibited greater precision. The PPP printer had the most accurate intra-arch measurements followed by the SLA printer, and therefore based on their high trueness and precision values, these systems were deemed to be the most accurate overall.

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