

# Evaluation of fit for 3D-printed retainers compared with thermoform retainers

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**Introduction:** In the literature, there is little information available on 3D-printed orthodontic retainers. This study examined the accuracy of 3D-printed retainers compared with conventional vacuum-formed and commercially available vacuum-formed retainers. **Methods:** Three reference models (models 1, 2, and 3) were used to fabricate traditional vacuum-formed, commercially available vacuum-formed, and 3D-printed retainers. For each model, retainers were made using the 3 methods (a total of 27 retainers). To determine the trueness, ie, closeness of a model to a true model, the distance between the retainer and its digital model at reference points were calculated with the use of engineering software. The measurements were reported as average absolute observed values and compared with those of the conventional vacuum-formed retainers. **Results:** Average differences of the conventional vacuum-formed retainers ranged from 0.10 to 0.20 mm. The commercially available and 3D-printed retainers had ranges of 0.10 to 0.30 mm and 0.10 to 0.40 mm, respectively. **Conclusions:** The conventional vacuum-formed retainers showed the least amount of deviation from the original reference models and the 3D-printed retainers showed the greatest deviation. However, all 3 methods yielded measurements within 0.5 mm, which has previously been accepted to be clinically sufficient. (Am J Orthod Dentofacial Orthop 2019;155:592-9)

Recent advances in digital dentistry have paved the way for the use of computer-aided design (CAD) technology in the modern orthodontic practice. Today, a 3-dimensional (3D) digital model, produced with an intraoral scanner, can be easily manipulated to perform the necessary measurements to facilitate diagnosis and treatment planning. In addition, digital technology eliminates the need for storage space and makes the retrieval and transfer of the models easier. Because of these advantages, it is speculated that 3D models will soon replace conventional plaster models.<sup>1-4</sup>

However, with the latest advancements in the digital manufacturing technologies, today, 3D printing makes it possible to directly fabricate dental and orthodontic appliances from 3D models.<sup>4-7</sup>

3D printing is a manufacturing process to fabricate 3D structures by joining material from a 3D model on a layer-by-layer basis.<sup>8</sup> Currently, there are a number of different 3D printers available in the market. The oldest and most established 3D printing technology is stereolithography (SLA) which consists of a bath of photosensitive resin, a model-building platform, and an ultraviolet laser to cure the resin.<sup>9,10</sup> Although the underlying technology of the SLA has largely remained the same, recent innovations have led to the next generation of printers that are smaller, less expensive, and more efficient than the original SLA printers.<sup>11,12</sup>

One of the most popular materials used for 3D printing technology is polymethylmethacrylate resin (PMMA). PMMA dental models fabricated with the use of a 3D printer can shorten the lead time and facilitate the production of multiple copies without distortions of anatomy.<sup>1</sup> Previous studies on the accuracy of printed models showed that 3D-printed dental casts are suitable for diagnosis and treatment planning.<sup>13,14</sup> Furthermore, Dietrich et al<sup>15</sup> evaluated the accuracy of 2 different 3D printing techniques for the physical reproduction of dental resin casts by using a comparative assessment of the digital files. The

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dimensional errors in the replicas were a maximum of 127  $\mu\text{m}$ , far below the reported guidelines for accuracy for orthodontic casts, which are 300–500  $\mu\text{m}$ .<sup>16,17</sup> In a recent study, Kim et al<sup>18</sup> also investigated dimensional differences between the 3D-printed and digital reference models. They evaluated the “trueness” of the printed models and defined “trueness” as the closeness of a model to a true value. It was shown that even the least accurate 3D printing method produced replica casts within 260  $\mu\text{m}$  of the reference models, still below the reported guidelines.

Although the increased accuracy of printed dental casts represents a large step forward in the advancement of 3D printing in dentistry, the “holy grail” of 3D printing for orthodontics is still a direct-printed clear retainer that is accurate, reproducible, and esthetic.<sup>19</sup> To directly fabricate an appliance such as a retainer or clear aligner, the digital scan of patients’ dentition can be used without a physical dental model. The first attempt to fabricate a retainer directly from a digital model was in 2014. Nasef et al<sup>20</sup> reported the successful fabrication of a retainer from an initial cone-beam computed tomography (CBCT) image, with no physical model, with the use of a selective laser sintering (SLS) 3D printer. Although the accuracy of the fabricated appliance was not evaluated, the study highlighted the potential uses of 3D printing in orthodontics. A recent study by the same investigators reported that the 3D-printed retainers were as accurate and reliable as the traditional vacuum-formed retainers.<sup>21</sup> However, comparisons between the 2 retainers were made based on the linear measurements performed manually with the use of digital calipers. Furthermore, the digital file used to fabricate the retainers was created from a CBCT image. It has previously been shown that the intraoral digital images generated with an Itero scanner are slightly more accurate than the ones produced from CBCT scans.<sup>2</sup> Also, 3D models produced from CBCT scans do not include gingival tissue.<sup>2</sup> Finally, owing to the use of an SLS printer in the study by Nasef et al, the printed retainer was white and opaque, which would be unacceptable to an orthodontic patient. Nevertheless, this investigation was one of the very first to show that it was possible to make retainers with the use of the 3D printing technology. In the literature, there have been other reports of successfully 3D-printed dental appliances, such as orthognathic surgical splints, implant guides, and indirect-bonding jigs; however, none of these studies evaluated the accuracy of the appliances made using this technology.<sup>5,22–24</sup> To date, there is little information on the fit of 3D-printed orthodontic retainers that are directly produced from digital intraoral images. Therefore, the purpose of the present study was to compare the trueness of 3D-printed and

conventionally fabricated clear retainers by comparing their fit with the original digital models. The null hypothesis was that there are no significant differences in the fit of 3D-printed clear retainer versus conventionally fabricated clear retainers and their corresponding reference models.

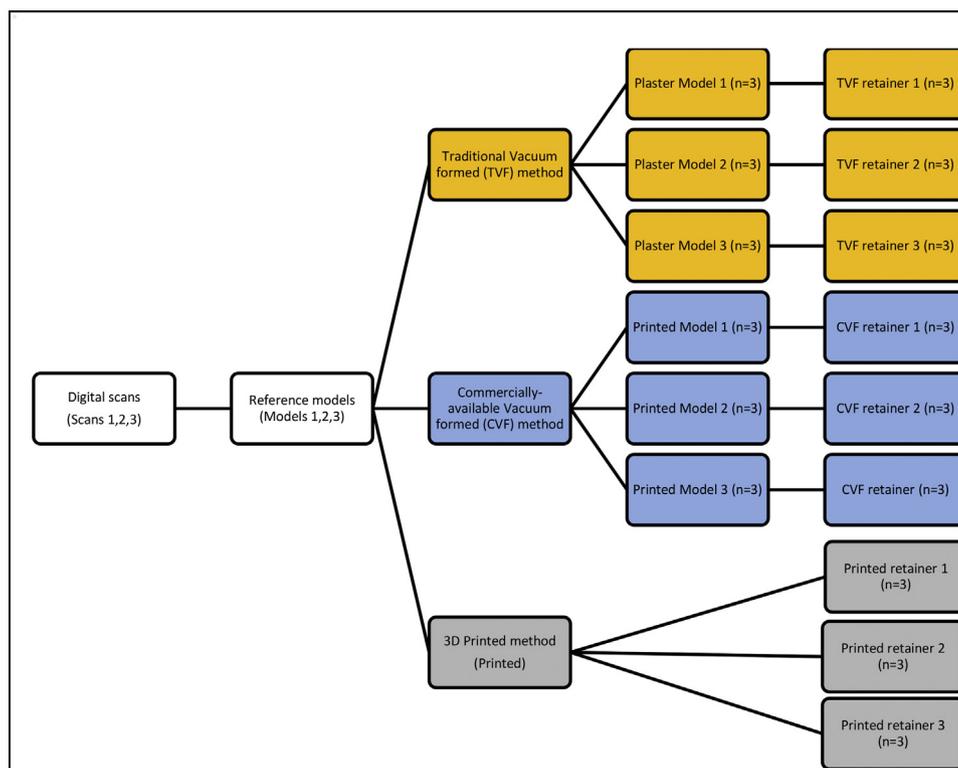
## MATERIAL AND METHODS

For this study, 3D digital scans of 3 different maxillary arches were selected from the digital orthodontic model archive at Virginia Commonwealth University Orthodontics clinic. All 3 arches had full complements of permanent teeth except third molars. Scan 1 and scan 2 were selected from the database of previously treated patients. Scan 3 was generated from a maxillary typodont. The study design is outlined in [Figure 1](#).

The three digital scans were first converted into the standard tessellation language (STL) file format, a data interface that is widely used in 3D printing and computer-aided manufacturing (CAM). The STL files of the 3 scans were then 3D printed (model 1, model 2, model 3) in an orthodontic lab (Accutech Orthodontic Lab) with the use of a polyjet style printer (Objet Eden 260VS; Stratasys, Eden Prairie, Minn). These 3D-printed replicates (model 1, model 2, and model 3) were used as reference models to ensure an equivalent starting point for the remainder of the study. Model 1, model 2, and model 3 were used to fabricate clear retainers with the use of 3 different methods: (1) traditional vacuum-formed method (TVF); (2) commercially available vacuum-formed method (CVF); and (3) 3D-printed (Printed) method. These 3 methods (TVF, CVF, and Printed) were completed 3 times for each of the 3 reference models for a total of 27 retainers ([Fig 1](#)).

For the TVF group, alginate impressions (Fast Set Identical alginate; Kerr Corporation, Orange, Calif) of models 1, 2, and 3 were poured up in regular set plaster (Henry Schein, Melville, NY) and a 1-mm plastic shell (Essix Plus; Dentsply International, York, Penn) was vacuum-pressed over the plaster models with the use of a thermoforming machine (Ministar; Great Lakes Orthodontics, Tonawanda, NY). Because the TVF retainers were made with the use of a standard technique according to the manufacturers’ instructions, they served as the criterion standard.

For the CVF group, models 1, 2, and 3 were digitally scanned with the use of an intraoral scanner (Itero Element; Align Technology, San Jose, Calif) and sent to Invisalign (Align Technology) for the fabrication of Vivera retainers. This process was completed by Invisalign, who 3D-printed a physical model from the digital scan and then thermoformed a retainer over the printed cast.



**Fig 1.** Process for design and fabrication of retainers. A total of 27 retainers with each reference model used to fabricate 3 retainers of each of the 3 methods.

For the Printed group, models 1, 2, and 3 were digitally scanned with the use of the 3Shape Trios scanner (Copenhagen, Denmark) and exported to the 3Shape software. The digital scan was then used to fabricate a “splint” in 3Shape’s Appliance Designer software. To limit any undercuts, a line of insertion was set and the retainer margin was drawn. The retainer thickness was set to 0.75 mm and “offset” was set to 0.25 mm to allow full seating of the printed retainer (Fig 2). The digital retainer was labeled with the model number and the file was saved (Fig 2). Once all of the digital retainers had been designed, the files were imported into Preform (Formlabs, Somerville, Mass), Formlabs’ software for preparing models for 3D printing. The retainers were oriented in the software to minimize cross-sectional peeling forces during printing and allow excess resin (Dental LT Clear; FormLabs) to drain. Support points were added to nonocclusal surfaces to maintain an accurate fit. The finalized retainer files were sent to the Form 2 3D printer (Formlabs) and printed with Dental LT Clear resin at a resolution of 100  $\mu\text{m}$ . After printing, the retainers were removed from the build platform and rinsed in 2 baths of 91% isopropyl alcohol for a total of 20 minutes and then allowed to air dry. Next, the retainers

were fully postcured in a cure chamber and the supports were removed (Fig 3).

After fabrication, the intaglio surface of the retainers and the occlusal surface of the original master casts were scanned with the use of the Itero Element scanner. To limit the light refraction from the clear retainers, an opaque CAD/CAM scanning spray (Henry Schein) was applied to the intaglio surface of the retainers. Models 1, 2, and 3 were scanned, and the STL files of the reference models and retainers were imported into engineering software (Netfabb; Autodesk, San Rafael, Calif) to analyze the fit of the 3D-printed retainers. This was done with the use of a “compare” feature in the Netfabb software. Setting each model as the “reference” and each retainer as the “comparison” allowed for direct analysis of the differences in 3 dimensions. The comparison tool found the shortest available distance in millimeters between the surface of the reference and the surface of the comparison part, and displayed the result in a color gradient and numeric values. From this comparison output, specific measurements were made at the specific landmarks to find the exact difference. The reference points chosen were similar to the ones used by Johal et al<sup>25</sup> in a study evaluating the fit of different thermoform materials (Fig 4).

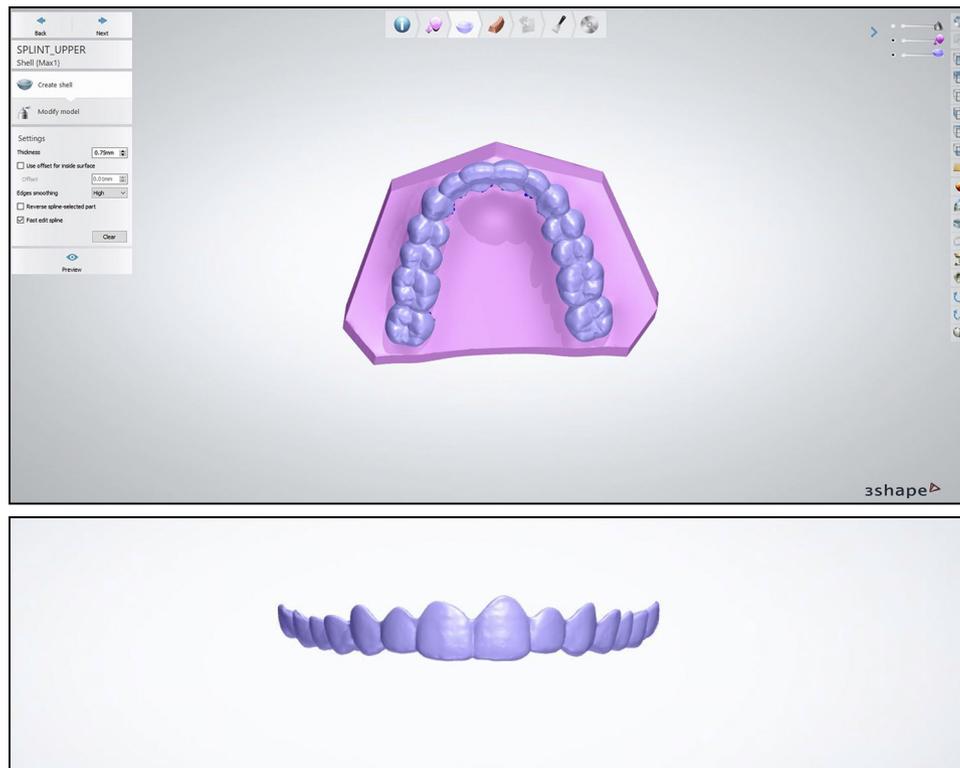


Fig 2. Appliance design.

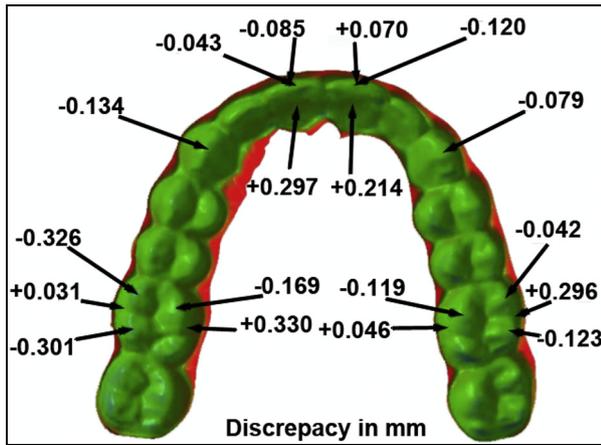


Fig 3. 3D printing process of the retainers.

The primary investigator completed the measurements at each of the 18 reference points for each retainer. An independent research assistant repeated the measurements and reliability was high (intraclass correlation coefficient 0.888). The average absolute observed distances between the retainer and its digital model were calculated to evaluate fit for each of the fabrication methods (TVF, CVF, and Printed).

**RESULTS**

For each reference point, the average absolute observed distances between the retainer and its digital model are given in Table and Figure 5. Average differences for the criterion-standard TVF ranged from 0.10 mm to 0.20 mm. This was slightly smaller than the ranges for CVF and the Printed retainers, which ranged from 0.10 mm to 0.30 mm and 0.10 mm to



**Fig 4.** Digital measurement of the fit of a retainer with the use of software.

**Table.** Summary of absolute differences from reference model by retainer and reference points

Reference point	Mean	95% CI	SD
<b>CVF</b>			
CT	0.20	0.10-0.31	0.21
IF	0.10	0.05-0.15	0.10
IIE	0.13	0.09-0.18	0.09
IL	0.30	0.21-0.39	0.18
MB	0.18	0.12-0.24	0.12
MDBC	0.24	0.14-0.33	0.19
MMBC	0.21	0.12-0.29	0.18
MMLC	0.25	0.15-0.34	0.20
MP	0.24	0.14-0.34	0.20
<b>TVF</b>			
CT	0.16	0.09-0.23	0.14
IF	0.13	0.10-0.17	0.07
IIE	0.11	0.05-0.17	0.11
IL	0.20	0.14-0.27	0.13
MB	0.12	0.07-0.17	0.10
MDBC	0.14	0.08-0.20	0.13
MMBC	0.10	0.05-0.16	0.10
MMLC	0.11	0.05-0.16	0.11
MP	0.17	0.09-0.24	0.15
<b>3D-Printed</b>			
CT	0.19	0.13-0.25	0.12
IF	0.26	0.18-0.34	0.16
IIE	0.10	0.07-0.13	0.06
IL	0.38	0.27-0.49	0.22
MB	0.21	0.12-0.30	0.18
MDBC	0.18	0.12-0.24	0.12
MMBC	0.15	0.09-0.20	0.11
MMLC	0.17	0.10-0.24	0.14
MP	0.40	0.29-0.51	0.22

0.40 mm, respectively. For all reference points, except the central incisor midfacial (IF) and central incisor mid-incisal edge (IIE), the TVF retainers had the smallest amount of deviation from the reference models, ranging

from 0.10 mm to 0.20 mm. The CVF retainers showed the least mean variance for the IF point (0.10 mm) but showed the greatest variance, ranging from 0.13 mm to 0.25 mm, at the canine cusp tip (CT), central incisor midincisal edge (IIE), first molar distobuccal cusp (MDBC), first molar mesiobuccal cusp (MMBC), and first molar mesiolingual cusp (MMLC). In the Printed retainers, less variation was seen at reference points located at the incisal edges and cusp tips (CT, IIE, MDBC, MMBC, MMLC), with mean variations of 0.10-0.19 mm from the reference models. However, the Printed retainers had higher average differences, 0.21-0.40 mm, for the reference points found on the smooth surfaces of the teeth, such as the central incisor midfacial (IF), central incisor midlingual (IL), first molar midbuccal (MB), first molar midpalatal (MP). Modified Bland-Altman plots demonstrate the actual differences (ie, both positive and negative) from the reference model for each retainer and each reference point (Fig 6).

**DISCUSSION**

At this point in time, the use of 3D printing in orthodontics has mostly been limited to the fabrication of physical models. In turn, research has focused primarily on the accuracy of these 3D-printed models and shown them to be clinically accurate for orthodontics across a number of different 3D printers.<sup>13-15,18</sup> However, little research has been done on the direct fabrication of clear orthodontic retainers by means of 3D printers.

The first attempt to fabricate retainers with the use of 3D printing technology was made by Nasef et al<sup>20</sup> in 2014. A few years later, the same authors evaluated the fit of the 3D-printed retainers.<sup>21</sup> In that study, digital calipers were used to measure the difference between the 3D-printed retainer and a vacuum-formed retainer. In the present study, software was used to superimpose the digital images of the printed retainers and their original models.

The TVF retainers were fabricated by an experienced technician and all of the manufacturer’s instructions were carried out in detail. Therefore, they served as a criterion standard to evaluate and compare the fit of the 3D-printed retainers. For the TVF retainers, the average deviations from the reference model were 0.10-0.20 mm, with the least difference for all but 2 of the reference points measured (IF, IIE). The CVF retainers were the next closest to the reference models, with average distances 0.10-0.30 mm. Finally, the Printed retainers showed the greatest deviation, with as much 0.40 mm deviation from the reference model. However, the Printed retainer group showed less difference at the reference points for incisal edges and cusp tips (CT, IIE,

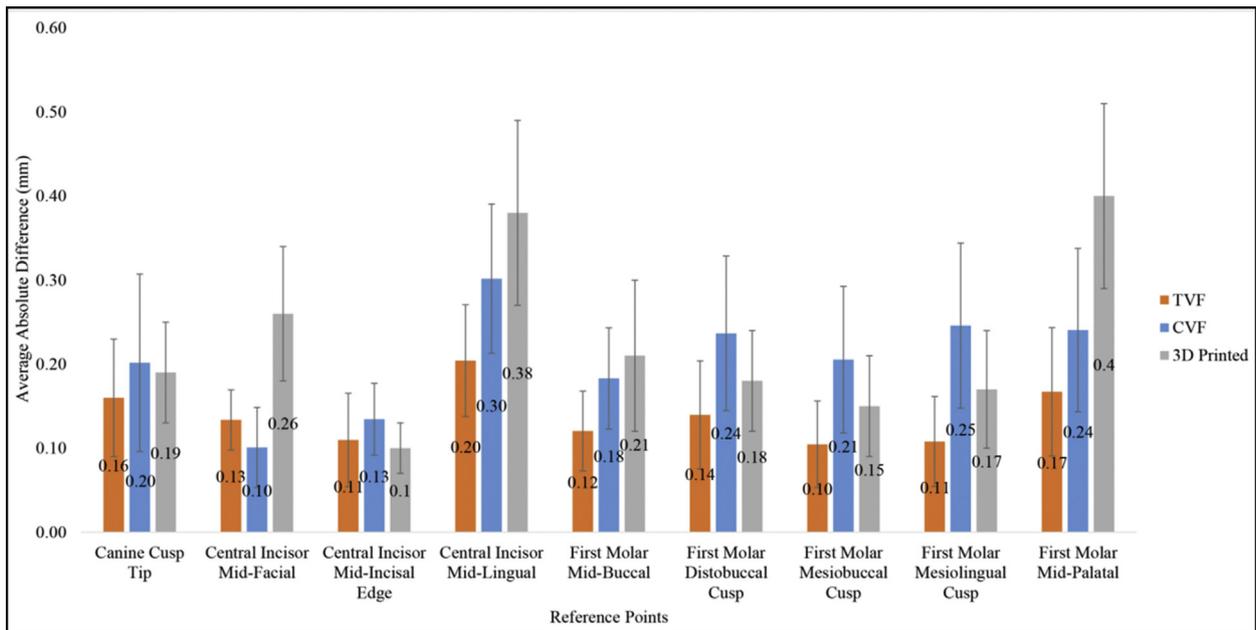


Fig 5. Average absolute differences in the fit of the retainers.

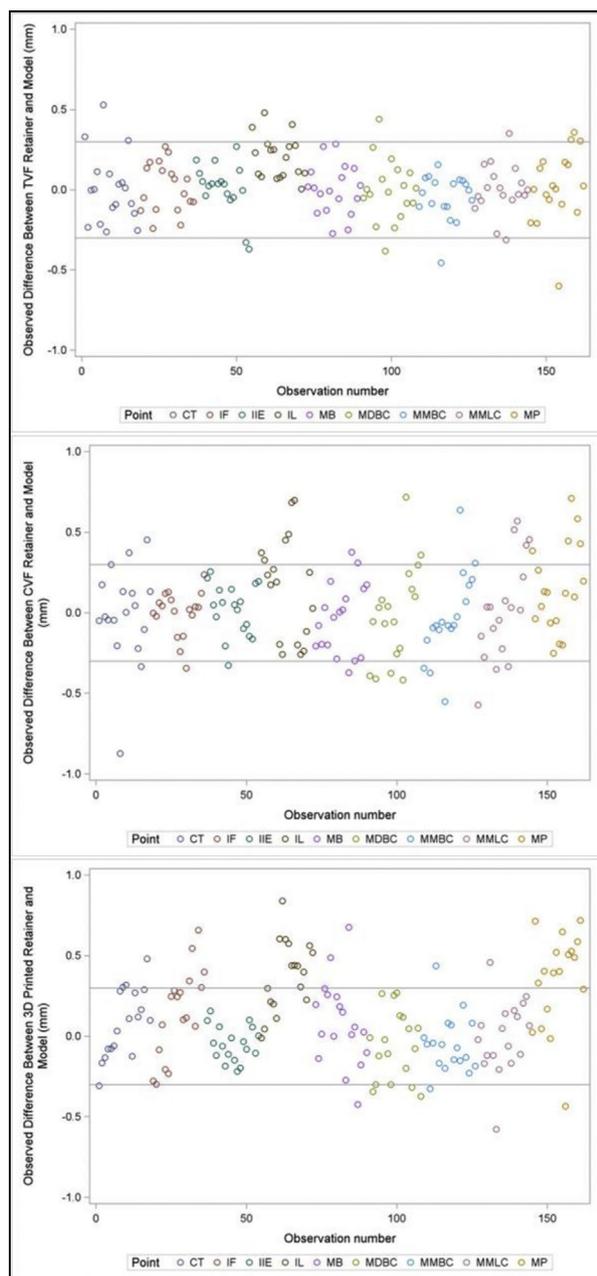
MDBC, MMBC, MMLC) and showed the most difference for the reference points located on the smooth surfaces of the teeth (IF, IL, MB, MP).

All 27 retainers were manually seated onto the reference models successfully and the fit was judged to be good and acceptable. In the literature, there is no information on the maximum acceptable distance between the clear retainers and their master casts to be accurate enough for clinical use. Therefore, in this study it was not possible to determine whether retainers fit accurately or not without a prespecified clinical threshold value. Instead, the fit was reported in terms of distance between the retainer and its reference model at preselected reference points. Having 2 clinically accepted and widely used retainer types (TVF and CVF) served as a guideline when evaluating the fit of the Printed retainers.

The Printed retainers were fabricated from ultraviolet (UV)-sensitive PMMA. It is very difficult to develop a clear and esthetic curable resin that is biocompatible, stable at body temperature, and strong enough to withstand the force of occlusion, and does not break down over time. In addition to these requirements, the 3D printing resin must have physical properties similar to the materials used for the fabrication of vacuum-formed retainers. Although the PMMA used in this study had some elasticity, it was anecdotally much more rigid than the thermoformed materials that make up the TVF and CVF retainers. The increased rigidity can cause issues when the retainer must flex over the heights of contours

of teeth or adapt to undercuts in the dentition. In the design stage for the Printed method, a line of insertion was selected as the path with the least amount of undercuts, but some undercuts persisted, primarily at the mid-facial and midlingual points of the central incisors and at the molars. Therefore, the largest differences between the Printed retainers and their master models at these same locations may be attributed to the rigidity of the resin used in this study (Figs 5 and 6). It is reasonable to assume that as the chemical makeup of UV-cured resins improve, 3D-printed retainers will acquire more flexibility. In the prototyping stages of this research, new PMMA resins were constantly being developed and we eventually selected a resin because of its compatibility with the 3D printer used in this study. A number of different companies claim that a clinically usable printed retainer is being developed and that the new materials have been optimized to match thermoformed retainer materials.<sup>26</sup> As new resins are developed, it may require special technology in the 3D printers themselves to leverage the advantages, which may make it difficult for individual clinicians to afford the printer technology and make the technology more applicable for a clear aligner manufacturer.<sup>19</sup>

Another factor specific to the Printed method was the offset. The term “offset” is not normally used in orthodontics but has applications in dentistry with the fabrication of full-coverage fixed or removable prostheses. For instance, when a crown is made for an analogous crown prep, the intaglio, or inside surface, of the crown can not



**Fig 6.** Modified Bland-Altman plots for differences between retainer and model: TVF (top), CVF (middle), and 3D-Printed (bottom).

be the exact accuracy of the tooth preparation or else the crown will not be able to fully seat. For this reason, there is some space added, offset, that is eventually filled with a dental cement. Initially, when prototyping the printed retainers, the offset was set to “0” and the resultant retainers could not be seated on the reference models. A pilot study to determine the minimum amount of offset

to allow full seating of the retainers had indicated that 0.25 mm would consistently allow for full seating. Therefore, an offset of 0.25 mm could account for a larger deviation of the printed retainers from the reference models. It is possible that, as a result of appropriate seating, the Printed appliances fit better than others in the incisal edges and cusp tips. This may also result in different clinical outcomes, which will need future studies to determine the effectiveness of 3D-printed appliances compared with conventionally fabricated ones.

A general limitation in the present study included the need to spray the intaglio surface of all retainers with a scanning powder so that the scanner could read the surface. Previous research states that scanning spray can account for 0.04–0.09 mm of thickness.<sup>27</sup> To eliminate the possible negative effect of the spray layer, all of the retainers were prepared by the same well trained operator under standard conditions.

The fit was measured with the use of software by superimposing the digital images of the retainers and their reference models. However, the alignment of the 2 images was done manually using the cusp tips and dental anatomy of the reference points. Operator error would have been improved with physical reference points added to the original reference models at the beginning of the study. These reference points might have aided in the alignment of the retainer and reference model scans as well.

Because there is no information on how much deviation from the original model would be considered clinically acceptable, it was not possible to determine equivalence in terms of the accuracy of the fit of the groups tested. Instead, the difference between the intaglio surface of the retainers and the occlusal surface of the reference model was evaluated to determine “true-ness.” In the literature, it has been previously denoted that measurements up to 0.50 mm are generally considered to be clinically acceptable for the evaluation of a digital articulation.<sup>16,17</sup> In this study, all of the retainers yielded measurements within 0.50 mm. However, future studies are needed to evaluate the accuracy of retainers.

The technology of digital dentistry and 3D printing is changing rapidly. An increasing number of orthodontists will adopt the technology, but improvements in printing materials will be necessary to produce accurate 3D-printed clear retainers that can be fabricated for clinical use.

## CONCLUSIONS

1. The traditional vacuum-formed retainers showed the least amount of deviation from the original reference models.

2. The 3D-printed retainers showed the greatest deviation at the reference points located on the smooth surfaces of the teeth but showed close adaptation at the incisal edges and cusps tips.
3. The 3D-printed retainers seem to be similar to the traditional vacuum-formed retainers in fit. Further clinical trials are needed to assess their clinical performance.

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