2022

The Effect of Crowding on the Accuracy of 3D Printed Aligners

Tonya Spangler

The Effect of Crowding on the Accuracy of 3D Printed Aligners

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

By

Tonya Spangler, DDS

University of Virginia, 2015

Virginia Commonwealth University, 2020

Thesis advisor

Eser Tüfekçi, DDS, MS, PhD, MSHA

Professor, Department of Orthodontics

Virginia Commonwealth University

Richmond, Virginia

May, 2022

Acknowledgements

I am abundantly blessed to have the support and guidance of my committee members through this process. Without the countless contributions and direction of Dr. Eser Tüfekçi, this research would not have been possible. She puts her heart, soul, and mind into her research, and is passionate about contributing to the research foundation and growth of this profession. Dr. Rami Ammoun spent countless hours helping me learn and troubleshoot the multiple software programs used in this study. Without his knowledge, I would have never been successful in coordinating all the steps involved. Dr. Caroline Carrico was vital in analyzing data and helping me to interpret the findings, always with the utmost kindness. A special thank you to my research assistant, Christina Gordon, for keeping me and the results of this research organized and accurate. Without Dr. Sompop Bencharit, the original idea for this project would not have been devised. His ideas and suggestions started the foundation of this research, and he was instrumental in creating the study design. Lastly, I would like to thank my family, friends, co-residents, and the VCU orthodontic and digital laboratory team for their endless support and encouragement as I navigated this final and most challenging feat in my academic accomplishments. My successes would not have occurred without any of you, and I will be forever grateful for that.

Table of Contents

Acknowledgements ii
Table of Contents iii
List of Tables iv
List of Figures v
Abstract vi
Introduction 1
Methods 8
Results 12
Discussion 18
Conclusion 25
References 26

List of Tables

Table 1. Summary Statistics for Average Deviation and RMS by Degree of Crowding and Fabrication Method 14

List of Figures

Figure 1. Evolving workflow of clear aligners. 5
Figure 2. Study design and workflow. 6
Figure 3. Workflow images. 7
Figure 4. Aligner superimposition with discrepancy scale. 11
Figure 5. Average Deviation by Fabrication Method and Degree of Crowding 15
Figure 6. Average Deviation by Method of Fabrication 16
Figure 7. Root Mean Square (RMS) by Fabrication Method 17
Figure 8. Superimpositions of moderate case #6. 17
Figure 9. Sensitivity of trimming intaglio surfaces on superimposition results. 24
Figure 10. Sites commonly seen with discrepancies in vacuum-formed aligners. 24
Figure 11. Sites commonly seen with discrepancies in 3D printed aligners. 24

Abstract

THE EFFECT OF CROWDING ON THE ACCURACY OF 3D PRINTED ALIGNERS

By: TONYA SPANGLER, DDS

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

Virginia Commonwealth University, 2022

Thesis Advisor: Eser Tüfekçi, DDS, MS, PhD, MSHA

Professor, Department of Orthodontics

Purpose: To evaluate the accuracy of three-dimensionally (3D) printed aligners compared to conventional vacuum-formed thermoplastic aligners with varying levels of dental crowding.

Methods: Digital intraoral scans of 10 different cases were assigned to their respective groups (n=10, each, 30 total) as follows: no crowding (control), moderate crowding, and severe crowding. Using 3Shape software, digital aligner samples were created in standard tessellation language (STL) file format and randomly 3D printed. The same STL files of each case were also sent to a dental laboratory for the fabrication of vacuum-formed samples, which is the current technology used for manufacturing aligners. The intaglio surfaces of aligners in both groups were scanned using cone beam computed tomography to create STL files, which were compared to the original STL files of the cases using Geomagic Control X software. Absolute deviations from the original file and root mean square values were recorded. A Kruskal-Wallis test was conducted to analyze the difference in average deviation and t-test was repeated for the RMS measure. Significance level was set at 0.05.

Results: The amount of crowding did not have an effect on the accuracy of aligners manufactured using 3D printing or conventional vacuum-forming techniques. 3D printed aligners showed less deviation than the vacuum-formed samples (0.1139mm vs 0.1330mm; p-value=0.0007). There was also a statistically significant difference in the variance between the two methods (p-value=0.0014), with a higher variance among aligners manufactured with the vacuum-forming technique than 3D printing method.

Conclusion: 3D aligners printed directly from an STL file exhibited better precision and trueness than the aligners fabricated using the conventional vacuum-forming technique. Since accuracy is defined as a combination of precision and trueness, it is concluded that direct printing from an STL file can be used to manufacture aligners.

Introduction

The advancements in digital technology and three-dimensional (3D) printing have revolutionized dentistry.[1-3] The clinical applications of modern dental technology include computer-aided design, computer-aided manufacturing (CAD/CAM), cone beam computed tomography (CBCT), digital X-rays, intraoral scanners and dental lasers.[3-6]

Intraoral scanners, CBCT, and 3D printers have transformed orthodontic profession for the better and has dramatically changed the face of patient care.[7-10] Consequently, digital orthodontic study models have quickly replaced traditional plaster casts because of their simplicity in obtaining accurate and reliable diagnostic information and ease in treatment planning with virtual setups and simulations.[7,8] The additional benefits of digital models include a decrease in laboratory procedures, material cost, and storage space. Improved communication among clinicians and patient comfort are also advantages of virtual models.[10,11]

Today, virtual models and CAD/CAM technologies combined with 3D printing are used for appliance fabrication such as aligners and retainers.[12] The current workflow for fabricating aligners consists of obtaining a traditional manual impression or a digital intraoral scan first, then pouring a plaster cast or printing a resin replica.

With clear aligners, orthodontic tooth movement is achieved with a series of trays vacuum-formed on a physical model where individual teeth were digitally or manually repositioned. Originally, an alginate impression needed to be repeated after each aligner for further repositioning.[12,13] Therefore, the fabrication and planning of these appliances were made using sequential wax set-ups. However, with the CAD/CAM technology, repeated impressions and wax set-ups are no longer needed, and this innovative technology is now routinely utilized for digital treatment planning and achieving sequential tooth movement for a complete aligner series.[13]

Today, numerous software programs are available to clinicians for fabricating in-house appliances, which gives the orthodontist more control in managing cases while reducing cost.[14] Specifically, these software systems allow practitioners to virtually plan and design aligners with a built-in feature that enables repositioning teeth, performing interproximal reduction, and placing attachments. Furthermore, with virtual set-ups, 3D models can be easily printed, and subsequently, appliances can be fabricated for each step of the aligner treatment.

Despite all the benefits the technology offers, 3D printed models are still required for each aligner to be manually manufactured by vacuum-forming.[2,12,14] The need for a physical replica still requires time, equipment, digital preparation of the model, and post-processing steps (Figure 1, A).[1,2]

First, after a digital impression is acquired with an intraoral scanner, an electronic file is created in the Standard Tessellation Language (STL) format, the standard configuration for 3D printing. The STL file is then sent to CAD/CAM software to prepare the model for 3D printing. The preparation process may include digitally trimming the excess material, creating a base, closing any holes that may cause printing errors, and hollowing the model to conserve the resin used for printing.[1] In addition to this tedious process, depending on the number of layers to be printed, the fabrication of a resin replica may take several hours.[1,15]

After printing, the post-processing of models also needs to be completed. While the exact steps depend on the manufacturer guidelines for a specific material, it typically includes washing and rinsing in an alcohol solution, additional light curing, and removal of printing supports.[1,2,15] Finally, once the 3D printed resin model is prepared, the aligner can be vacuum-formed on this replica. Afterward, the model and excess aligner material trimmed away during manufacturing are discarded. Therefore, the need for a resin model to fabricate aligners is not only labor-intensive but also environmentally unfriendly due to excessive plastic material use.

With recent advancements in polymer chemistry and materials science, 3D printing of orthodontic aligners directly from STL files is now possible.[16,17] The process which consists only of intraoral scanning, digital treatment planning, and 3D printing could offer a more efficient and streamlined workflow by eliminating the extra procedure necessary to create a physical model (Figure 1, B).[16,17] In addition, the technique would eliminate the additional pre-and post-processing steps for models and aligners, thus reducing waste because of less material use and precise printing of the appliance.[18]

Previous studies on direct printed retainers have shown that the appliances were accurate and reliable compared to conventionally vacuum-formed retainers.[19,20] Similarly, a 2019 study by Cole et al.[21] on the accuracy of 3D printed retainers has shown that direct printed retainers were accurate within 0.5mm tolerance level, which was deemed clinically acceptable. Lastly, Jindal et al.[24] compared the geometric and mechanical properties of 3D printed aligners to those of conventional vacuum-formed aligners. The authors reported that printed aligners were more accurate and mechanically stronger when fabricated from a resin material suitable for direct printing.

Although the accuracy and precision of 3D printed retainers have been previously investigated, there is limited information on the accuracy of direct-printed aligners. Furthermore, one of the most significant limitations of the previous work is that studies were conducted on aligners fabricated from the only available resin at the time (Dental LT Clear Resin; Formlabs

Inc.; Somerville, MA), formulated for manufacturing occlusal splints. To date, there are only a few studies on the accuracy of aligners directly printed from a suitable resin.[16,17]

Zinelis et al.[16] compared aligners printed with a new commercially available resin, Tera Harz TC-85DAC (Graphy Inc; Seoul, Korea), suitable for direct printing. The authors reported that the mechanical properties of aligners depended on the type of 3D printer technology used. In a more recent study, Koenig et al.[17] also used this new resin to fabricate aligners to evaluate the accuracy of direct printed appliances. A maxillary arch with moderate crowding was used as a reference model. The results indicated that direct printed aligners had greater trueness and precision than thermoformed appliances. It is not clear if the amount of crowding plays a role in the accuracy of direct printed aligners, and until now, the study by Koenig et al.[17] is the only one that attempted to direct print appliances of a crowded arch using the suitable new resin.

In light of promising results of previous research, it is plausible that 3D printing technology would soon become the method of fabricating clear aligners directly from STL files of the arches.[15-17,21,26] With the availability of a new resin material specifically formulated for printing aligners, this research aims to evaluate the effect of dental crowding on the accuracy of printed aligners. Specifically, the accuracy of aligners directly printed from STL files of orthodontic cases with no crowding, moderate, and severe anterior crowding will be compared to their original digital file.

A.

B.

Figure 1. Evolving workflow of clear aligners. A) Current workflow of fabricating clear aligners and B) the future reduced workflow of directly printing clear aligners.

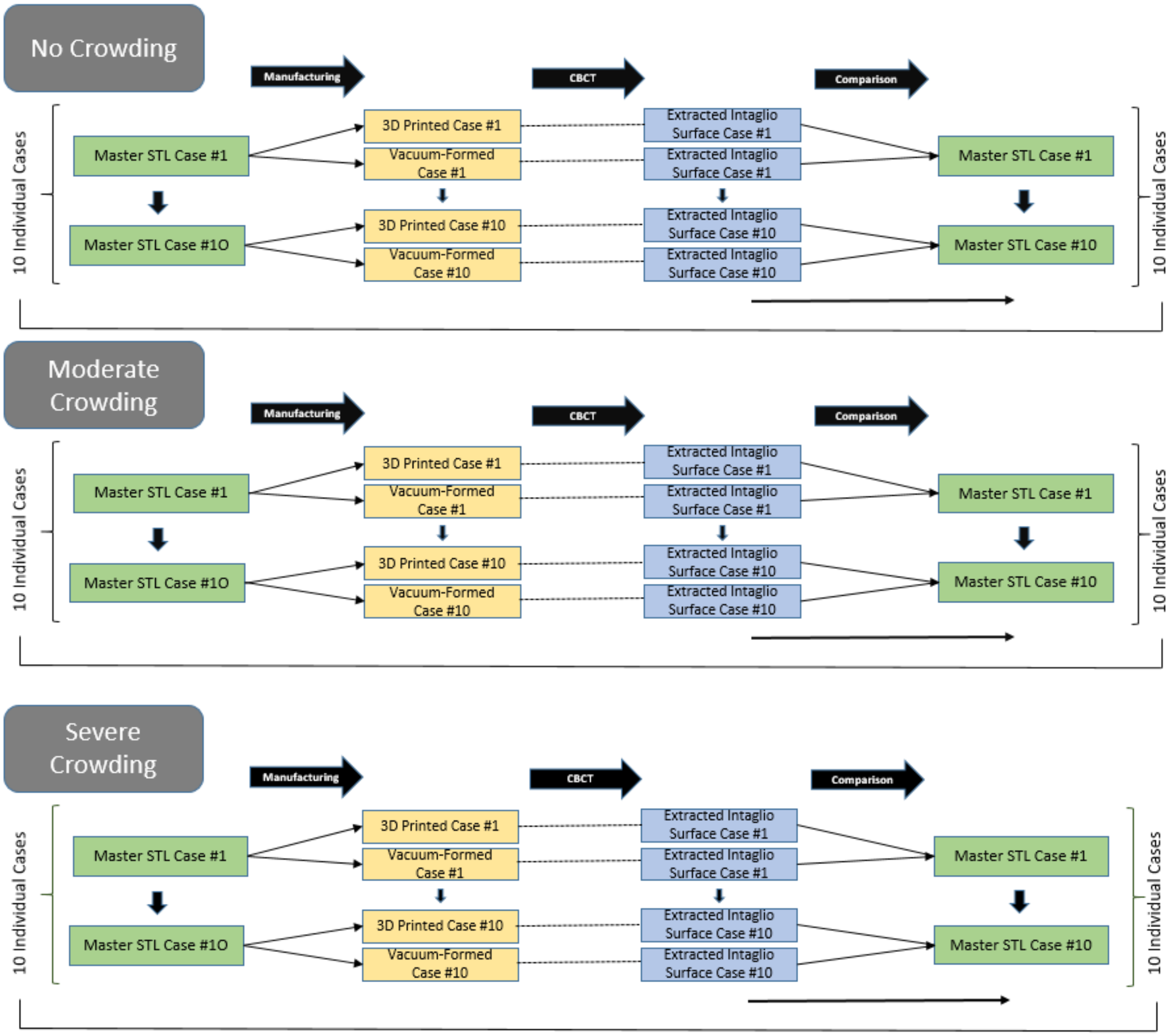

Figure 2. Study design and workflow. The study design and workflow of 30 individual cases with different levels of crowding present.

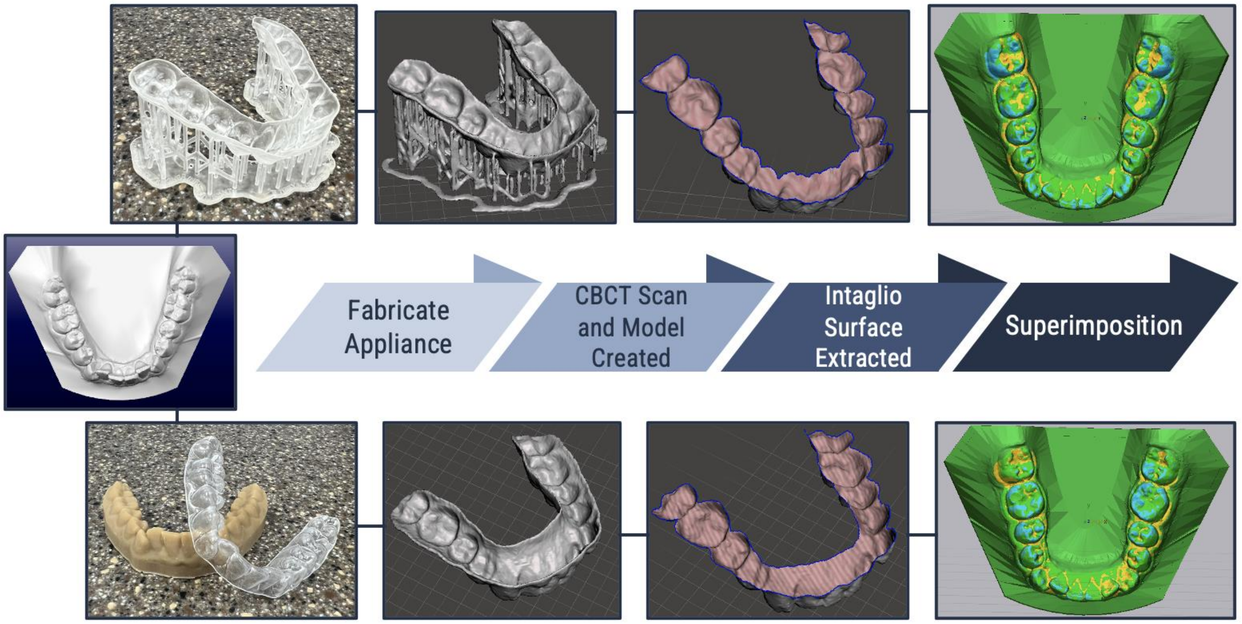

Figure 3. Workflow images. Illustration of workflow starting with the original digital model to fabrication of the aligner, model conversion from the CBCT, extraction of the intaglio surface, and superimposition to the original file.

Methods

Digital intraoral scans from the VCU orthodontic clinic patient database were evaluated for mandibular anterior crowding (canine to canine). Ten different cases were assigned to their respective group (n=10, each) as follows: no crowding (ideal alignment), moderate crowding (4-6mm), or severe crowding (6.1-10mm). Cases with missing dentition, significant posterior crowding, a bonded lingual retainer, and excess plaque or residual resin visible in the digital image were excluded during the selection process. The initial selection process was carried out first by one of the previously calibrated clinicians. The second clinician independently evaluated the cases, and if there was no agreement (only 3 out of 45 scans), the two clinicians convened to complete the case selection process together.

Digital scans previously acquired from an iTero scanner (Align Technology, San Jose, CA) of each case were imported into 3Shape software (Copenhagen, Denmark) in the STL file format. The 3Shape Appliance Designer software was used to digitally design an aligner for each specific case. The aligner thickness was set to 0.65mm, and wax block-outs of undercuts were digitally removed. Samples from each group were randomly printed in groups of six at a 30-degree angulation using the Form-3B stereolithography printer (Formlabs Inc.; Somerville, MA) and Formlabs Dental LT Clear Resin (Formlabs Inc.; Somerville, MA). The post-processing procedures were carried out according to the manufacturer's instructions, which consisted of rinsing in 96% isopropyl alcohol for 5 minutes and air drying, followed by ultraviolet light curing for 20 minutes at 80°C.

The duplicate original STL files of the cases were also sent to a local dental laboratory to simulate the current technology used to fabricate clear aligners, which consisted of 3D printing of a resin model of each unique case, and subsequently vacuum-forming the appliance on this replica. The dental laboratory was directed to avoid using wax to block out undercuts and adhere to the same manufacturing conditions for all samples. One experienced laboratory technician made all the vacuum-formed aligners.

A CBCT scan was then obtained of the 3D printed and vacuum-formed aligners for each case (STL #1 printed and STL #1 vacuum-formed; STL #2 printed and STL #2 vacuum-formed, etc.) in each group. The CBCT scanning parameters were based on previous research by Ammoun et al.[27], using CBCT (iCAT FLX version 10) with standard postoperative implant scan parameters (16cm x 10cm volume, 0.3mm voxel size, 4.8-second scan time, 2.0-second exposure time, 120 kVP, 5 mA, and 283, 582, or 291 mGy/cm2). The study design and workflow is shown in Figure 2.

The DICOM files created by the CBCT were then converted to a model in STL file format using 3D Slicer (3D Slicer, National Institutes of Health, Bethesda, MD). The models were used to manually trim and extract the intaglio surface using Autodesk Meshmixer software (Autodesk, Inc., San Rafael, California). The STL files of the intaglio surfaces created from the converted CBCT images were then imported into Geomagic Control X software (3D Systems, Rock Hill, SC) for further analyses. The STL files of the printed aligner and the vacuum-formed aligner intaglio surfaces were individually compared to the original STL file of the arch being examined. The files were first oriented using the Transform Alignment feature, where three similar points were selected to roughly superimpose the files, and then were superimposed using the Geomagic Control X software's best-fit model analysis using an error of 0.5mm and 25%

sampling. Figure 3 contains images of the individual steps. Deviations from the original scan and the CBCT scan of the aligners were recorded. The absolute average discrepancy was used to examine the accuracy. It was calculated by multiplying the average negative discrepancy by (-1), adding it to the average positive discrepancy which was then divided by the sum of 2 as described in Ammoun et al.[28] Overall trueness was determined by the root mean square value (RMS) which takes into account absolute differences between reference and measured values at each point in the model. The color map of the superimposition showing the differences between the reference and measured values was set to 100-micron tolerance. Positive deviations, or measured points that are larger than the reference file, are scaled to red, while negative values represent measured points that are smaller than the original file (Figure 4).

STATISTICAL ANALYSIS

Descriptive statistics were analyzed using means for the absolute average deviation. A two-way analysis of the variance (ANOVA) model with interaction term was used to assess the effect of crowding on the differences in the two fabrication methods; vacuum-formed and 3D printed. Based on the results of this model, an individual unequal variance t-test was used to evaluate the difference between the printed and vacuum-formed aligners. Nonparametric analyses were also considered due to the influence of soft tissue present and trimming of the virtual models. A Kruskal-Wallis test was conducted to determine the difference in average deviation between the 3D printed and vacuum-formed aligners. The t-test procedure was also repeated for the RMS measure. Significance level was set at 0.05 and SAS EG v.8.2 (SAS Institute, Cary, NC) was used for all analyses.

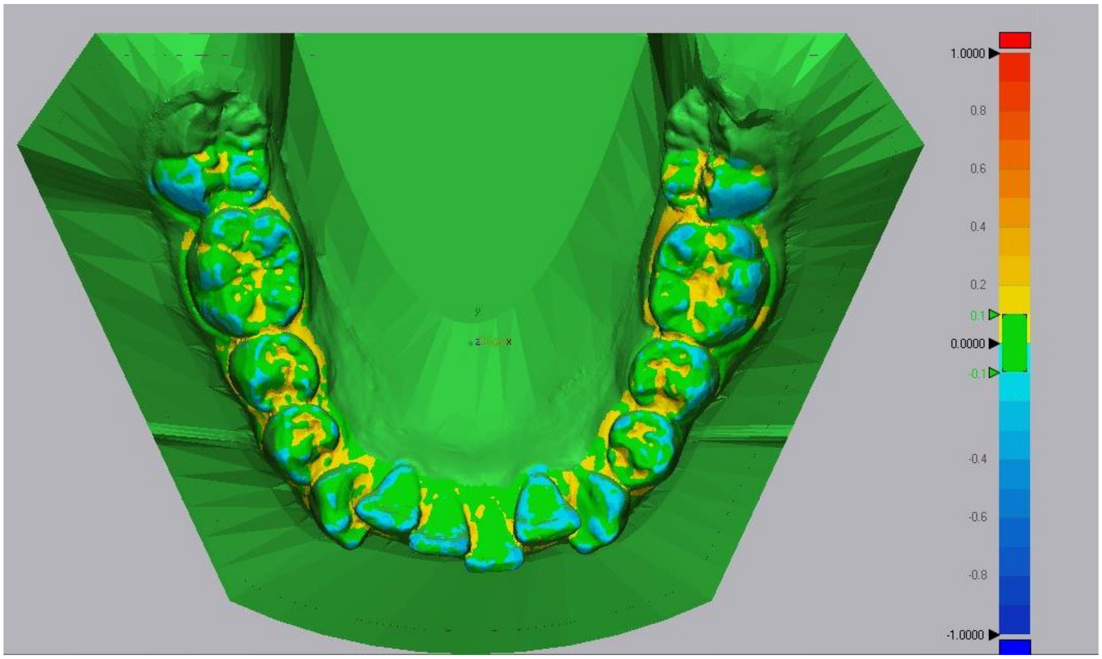

Figure 4. Aligner superimposition with discrepancy scale. Superimposition with scale representing the degree of positive or negative deviation from the original intraoral scan.

Results

The results of the superimposition measurements are provided in Table 1. For the 3D printed aligners, average absolute discrepancy was 0.12 ± 0.01mm, 0.11± 0.01mm, and 0.11 ± 0.01mm for the no crowding, moderate crowding and severe crowding groups, respectively, whereas for the vacuum-formed group, the values were 0.13 ± 0.03mm, 0.13 ± 0.02mm, and 0.13 ± 0.02mm. The RMS values for the 3D printed aligners were 0.15 ± 0.02 for all three crowding groups. For the vacuum-formed aligners, the RMS values were 0.17 ± 0.04, 0.17 ± 0.03, and 0.17 ± 0.03 for the no crowding, moderate crowding, and severe crowding groups, respectively. Analysis of two-way ANOVA demonstrated that the difference between 3D printed and vacuum-formed aligners was not dependent on the degree of crowding (p-value=0.9464). The main effect for crowding was also not statistically significant (p-value=0.9600). However, the manufacturing method was found to have a statistically significant effect (p-value=0.0007). Aligners fabricated through 3D printing were on average, 0.02mm lower in terms of average deviation than aligners that were vacuum-formed (0.1139mm vs 0.1330mm; p-value=0.0007) (Table 1).

Since the only significant factor was the method of fabrication, a t-test was performed to evaluate the differences in the two methods. There was a statistically significant difference in the variance between the two groups (p-value=0.0014), with a higher variance among vacuum-manufactured aligners than 3D printed (SD=0.0247 vs 0.0133, p-value=0.0014). The results of the unequal variance t-test again demonstrated a statistically significant difference between the two methods, with an average difference of 0.0191 (p-value=0.0005) (Figure 5 and Figure 6).

A nonparametric analysis was also conducted to reduce the influence of outliers in the data caused by sensitivity of trimming soft tissue in the virtual models. This analysis also demonstrated a statistically significant difference in the average deviation of the two fabrication methods (p-value=0.0009).

The results were similar with the outcome metric of RMS. Again, the vacuum-formed aligners had significantly greater variability (SD= 0.035 vs 0.018, p-value=0.0015) and significantly greater average RMS (0.149 vs 0.174, p-value=0.0015). Figure 7 displays the distribution of RMS for the two manufacturing methods.

Representative images of a superimposition using the 3D Comparison feature are shown for sample #6 with moderate crowding in Figure 8. The green areas represent high trueness or no deviation from the original STL file. In this case, the vacuum-formed aligner showed more yellow in the anterior region, indicating a positive deviation or bigger sample up to 200 microns compared to the original file. Conversely, the 3D printed aligner showed posterior areas of negative deviation (smaller sample) up to 600 microns, represented in blue. The remainder of the superimpositions were similar in trueness.

Table 1. Summary Statistics for Average Deviation and RMS by Degree of Crowding and Fabrication Method

Fabrication Method	Degree of Crowding	Average Deviation, mm (Mean, SD)	RMS (Mean, SD)
3D Printed	None	0.12, 0.01	0.15, 0.02
	Moderate	0.11, 0.01	0.15, 0.02
	Severe	0.11, 0.01	0.15, 0.02
Vacuum-formed	None	0.13, 0.03	0.17, 0.04
	Moderate	0.13, 0.02	0.17, 0.03
	Severe	0.13, 0.02	0.17, 0.03

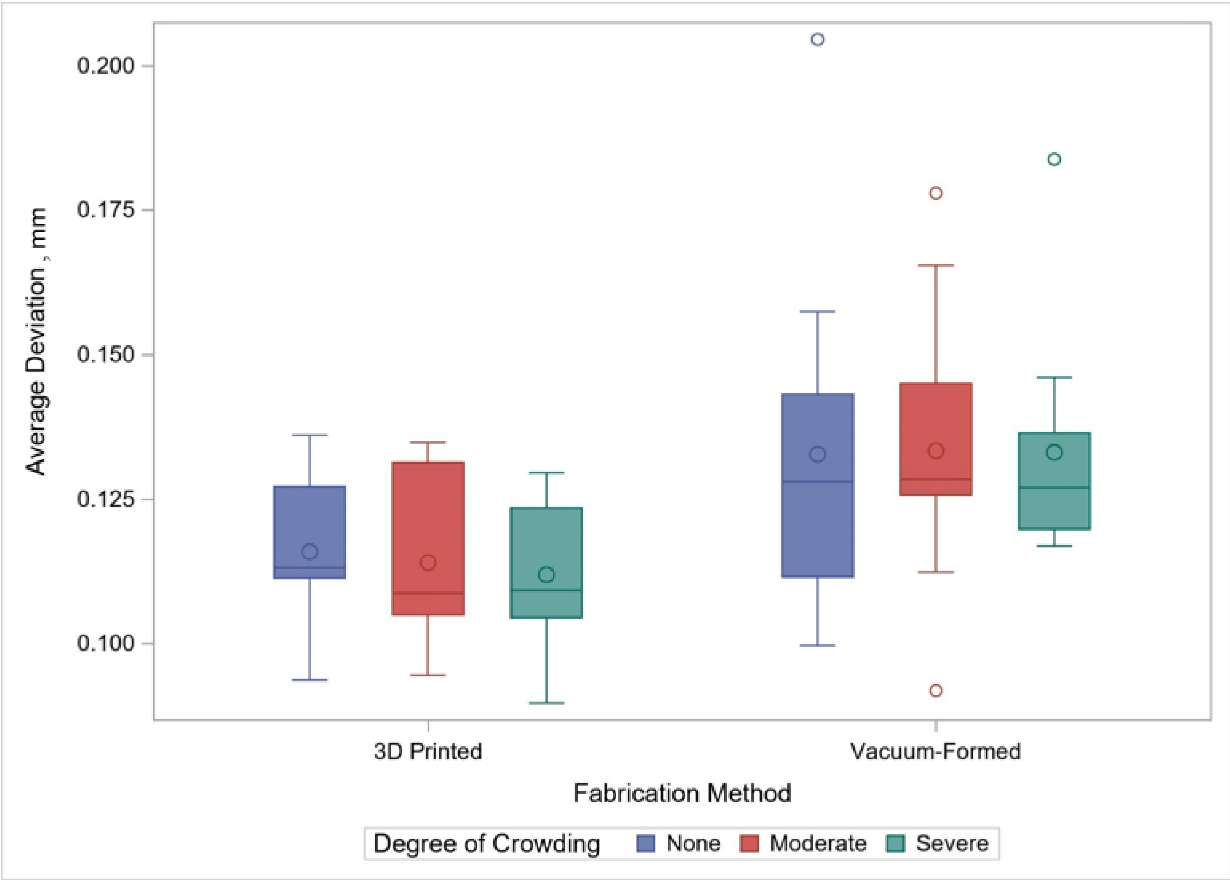

Figure 5. Average Deviation by Fabrication Method and Degree of Crowding

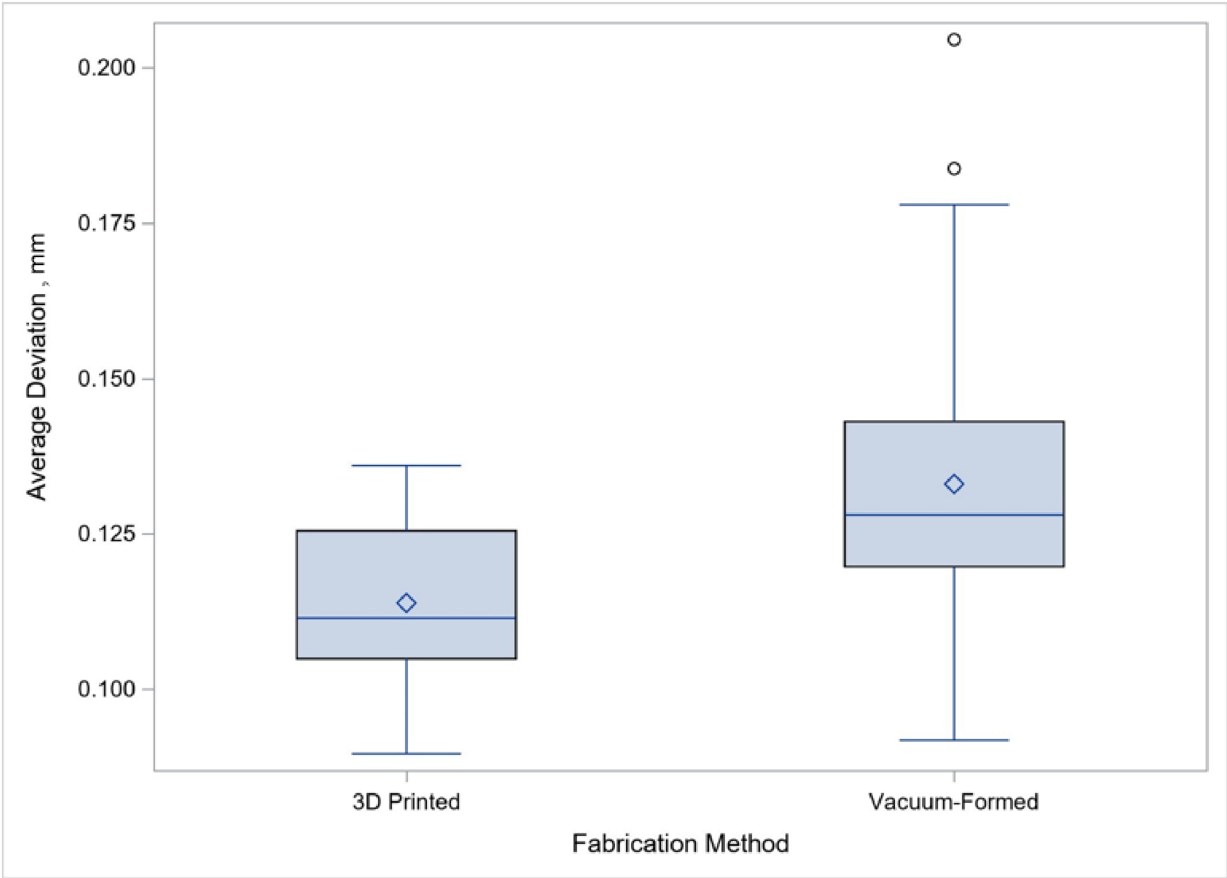

Figure 6. Average Deviation by Method of Fabrication

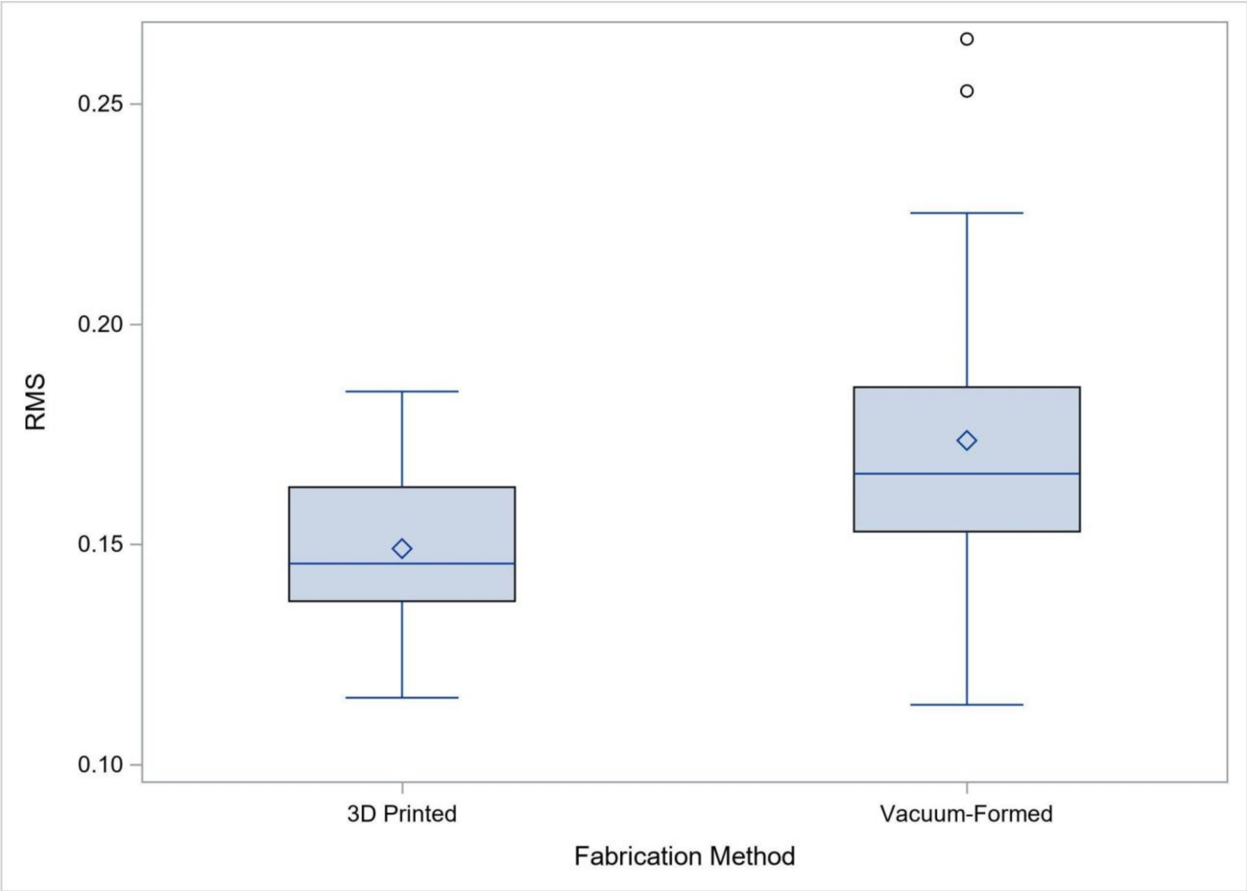

Figure 7. Root Mean Square (RMS) by Fabrication Method

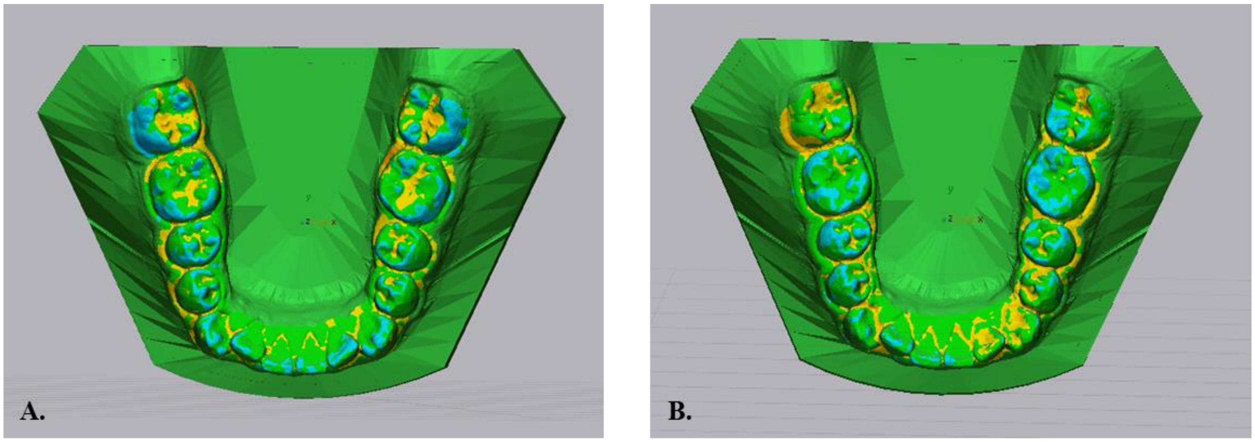

Figure 8. Superimpositions of moderate case #6. A) 3D printed and B) vacuum-formed superimpositions of moderate case #6.

Discussion

New emerging technologies and materials may soon allow clinicians to directly 3D print retainers or aligners, which could greatly increase the autonomy of the orthodontist, reduce manufacturing and materials costs, reduce waste, and expedite the process of treating patients with aligners.[14,16,17,19,20] In addition, the precise fabrication of aligners can improve patient comfort with softer more ideal margins, and they can be reproduced identically and uniformly for each aligner without the manufacturing variation that is inherent with thermoplastic aligners.[18]

In this study, deviations between the printed and vacuum-formed aligners were similar to previous studies.[17,24] The mean average absolute discrepancy was 0.11mm $\pm$ 0.01mm for the moderate and severe crowding groups. Koenig et al.[17] reported a mean absolute value range of 0.079mm to 0.224mm in their study, which used one reference model with moderate crowding. The standard deviation of that study was larger than the current one (0.054 vs. 0.01). Similarly, Jindal et al.[24] also noted comparable values with 0.21mm for the printed aligners as opposed to 0.37mm for the thermoformed samples. In the current study, both the accuracy and precision of printed aligners were higher than the values in previous studies.[17,24]

With the growing body of literature demonstrating the clinical usefulness of 3D printing in orthodontics, additional studies have been conducted to develop and improve upon the concept. Studies by Naeem et al.[15] and Williams et al.[26] have investigated how accuracy and precision of 3D printed retainers can be influenced when using various types of 3D printers and using different print angulations, respectively, in order to develop the process and ensure the most accurate application.

According to Naeem et al.[15], different printing technologies resulted in significant differences in trueness and precision between the 3D printed retainer groups. For example, while stereolithography and polyjet photopolymer printers yielded samples showing high trueness, the digital light processing groups exhibited higher precision. The printer utilized in the current study is based on stereolithography technology. Therefore, future studies using printers with different technologies should be investigated.

Williams et al.[26] investigated the effect of the printing angle on the trueness and accuracy of the printed retainers. Using a stereolithography printer, retainers that were 3D printed were found to be accurate within 0.25mm at all angulations: 15, 30, 45, 60, and 90 degrees. Since most manufacturers recommend printing models at 30 degrees or less, and retainers were shown to be accurate at all angulations, printing at 30 degrees was selected for this study. This allowed 6 aligners to be printed at once. The ability to increase the printing angle to accommodate more retainers at once is important, as it would save time and cost during the manufacturing process. Future studies investigating the trueness and precision of printed aligners with approved materials are therefore warranted to maximize efficiency while ensuring accuracy.[26]

Previous research on vacuum-formed aligners, which is the traditional method of fabricating these appliances, has demonstrated that the manufacturing can alter the ideal thickness, uniformness, and other characteristics of the plastic material, therefore influencing the mechanical and functional properties of the aligners. In a 2018 study by Ryu et al.[29], four common thermoplastics materials used to fabricate orthodontic aligners were evaluated before and after thermoforming, and changes in transparency, water absorption and solubility, surface hardness, flexure and elastic moduli, and tensile and flexural forces after manufacturing process were noted. These modifications in the material characteristics can play a role in the force systems applied to the teeth during treatment with clear aligners.[24,25,29] While similar post-processing steps can also alter material characteristics with 3D printed aligners, there may be less operator error and more control in designing features like customized thickness. Fabrication under well-controlled conditions may result in more accurate aligners; however, direct conclusions regarding material characteristics need further evaluation comparing an approved polymer for the fabrication of aligners.

Except for the research by Zinelis et al.[16] and Koenig et al.[17], all previous studies on 3D printed aligners, including the present study, used a polymer resin that was not specific to aligner printing. Furthermore, all 3D printed aligners evaluated in this study were manufactured from one type of printer using stereolithography technology. SLA printers were the first type of 3D printer established and are still widely used in orthodontic offices. This printer type contains a liquid resin into which a build platform is slowly lowered, being cured each time additional material covers the last layer by an ultraviolet laser. Another common printer type, digital light processing (DLP), operates similarly to SLA printers but may be more efficient, as they cure an entire layer at once, rather than a single laser beam tracing an outline of the object to cure it as with an SLA printer. Fused deposition modeling and polyjet photopolymerization (PPP) printers can also be found in orthodontic offices, and all have proven to be accurate and precise.[1,15]

Despite the accuracy demonstrated in the various 3D printer types, research has demonstrated different strengths and greater accuracy held by certain printer types.[1,15] A comparative study by Kim et al.[30] examined the precision and trueness of 3D printed models on different 3D printer types and found that PPP and DLP techniques were more precise than SLA printers. However, when Naeem et al.[15] compared aligners printed from various 3D printer types, it was determined that PPP and SLA were the most accurate overall. While SLA printers have been deemed to be accurate and precise, this could be considered a limitation in the present study.

An important consideration for directly printing aligners is the manufacturer's recommendation for the printer type most suitable for the material. The only approved material, Tera Harz TC-85DAC (Graphy Inc; Seoul, Korea), when evaluated by Zinelis et al.[16], showed significant differences in all mechanical properties when printed from five different printers. With future aligner materials, it will be important to follow the manufacturer's guidelines to ensure optimal material characteristics.

Another possible limitation in the present study is inherent in the extraction of the intaglio surfaces. Since all thirty cases were different in their anatomy and distribution of the crowding, trimming the models to exclude all the soft tissue interproximal areas was not possible. Additionally, some vacuum-formed aligners were trimmed at the cervical portion of the anterior teeth, eliminating a small portion of the tooth surface to be sampled. To account for the differences between cases, the trimmed intaglios surfaces for each sample were compared to each other to ensure they were comparable in the area they included for superimposition. To improve this further, all samples could be trimmed and scalloped interproximally to eliminate any soft tissue interferences that may affect the comparison of tooth adaptation. Figure 9 highlights the sensitivity of the trimming. The original trimmed surface showed a 1mm discrepancy at the lower right retromolar pad that was retrimmed to eliminate the soft tissue discrepancy.

Both fabrication methods in this study showed more deviation on second molars when they were present. More intricate occlusal anatomy or contamination of the area with saliva and plaque during the initial intraoral scan may be contributing to this observation. The areas frequently seen with the most deviation within the vacuum-formed group were in the anterior interproximal, facial, and lingual surfaces with moderate to severe crowding (Figure 10). This may be due to undercuts from the labial and lingual axial inclinations of the teeth not allowing surface adaptation during vacuum-forming. Conversely, buccal surfaces of posterior teeth showed the most significant discrepancies in the 3D printed aligners (Figure 11). This could be due to errors in the printing or post-processing curing process of the models causing shrinkage of the material in those areas.

While the results of the study show statistical significance in terms of trueness, the extent of clinical significance is less, indicating that both methods of fabrication may be sufficient for ideal treatment outcomes, regardless of the level of crowding present. The level of clinical significance in similar studies has ranged from 0.25mm to 0.5mm.[21,22,31] For the most ideal control of tooth movement, no space would exist between the aligner material and tooth, but space from 0.15mm to 0.25mm has been deemed acceptable to provide activation within the limitation of aligners.[31] The mean difference of 0.02mm between the thermoplastic and 3D printed aligners is unlikely to contribute to inferior outcomes. Nonetheless, the findings of this study support the equivalency or potential superiority of directly printing aligners, irrespective of the amount of crowding present. These results are promising that printed aligners may soon replace traditional vacuum-formed aligners due to their ease of fabrication and potential to be more accurate and comfortable for patients. Further studies are indicated to evaluate the physical, mechanical, and dimensional properties as approved aligner resins become more widely available. This would be valuable to compare not only to traditional vacuum-formed aligners, but also to the 3D printed aligners from commercially available dental resins, as used in many of the studies discussed.[15,19,20,24-26]

The fit of 3D printed aligners in a clinical setting should also be evaluated in future studies. While assessing the fit clinically would give consideration to the oral environment and periodontal ligament response to pressure, this method of evaluation is difficult to execute and interpret. Therefore, previous studies evaluated the fit of aligners by investigating the surface adaptation of the appliance to its dental model. Analysis of surface adaptation would be a more realistic approach to determine the fit of aligners. Lombardo et al.[32] evaluated the fit of aligners by calculating the gap volume between the aligner and model of several different thermoplastic materials using high-resolution micro-computed tomography. Mantovani et al.[33] did a similar investigation using scanning electron microscopy to evaluate the discrepancy. Both studies revealed discrepancies of similar magnitude to the present study. If resins suitable for printing aligners are similar in characteristics to thermoplastic materials placed over a dental model, comparable or reduced gap measurements would be expected.

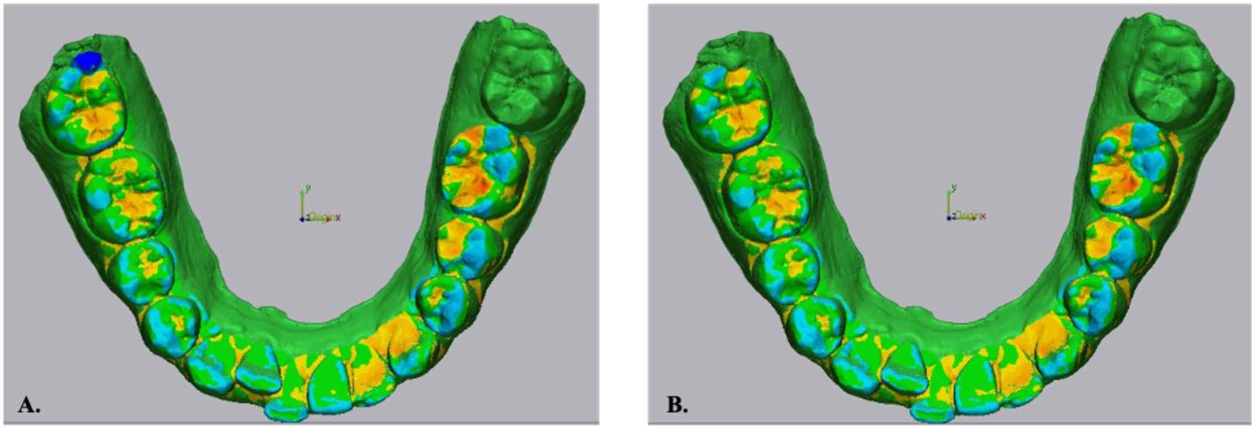

Figure 9. Sensitivity of trimming intaglio surfaces on superimposition results. A) Sample #5 from the vacuum-formed moderate crowding group , B) the same sample re-trimmed to exclude the lower right retromolar pad tissue that showed a 1mm discrepancy from the original intraoral scan.

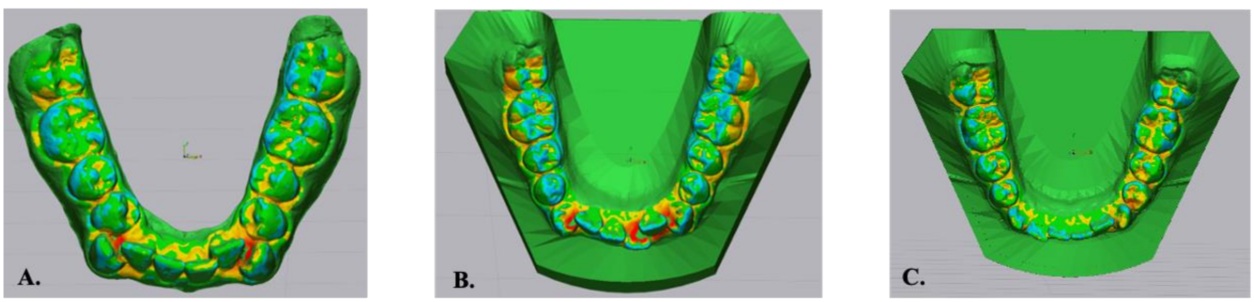

Figure 10. Sites commonly seen with discrepancies in vacuum-formed aligners. Severe (A. and B.) and moderate (C.) vacuum-formed cases displaying positive discrepancies of up to 1mm, represented in red, in interproximal, facial, and lingual areas.

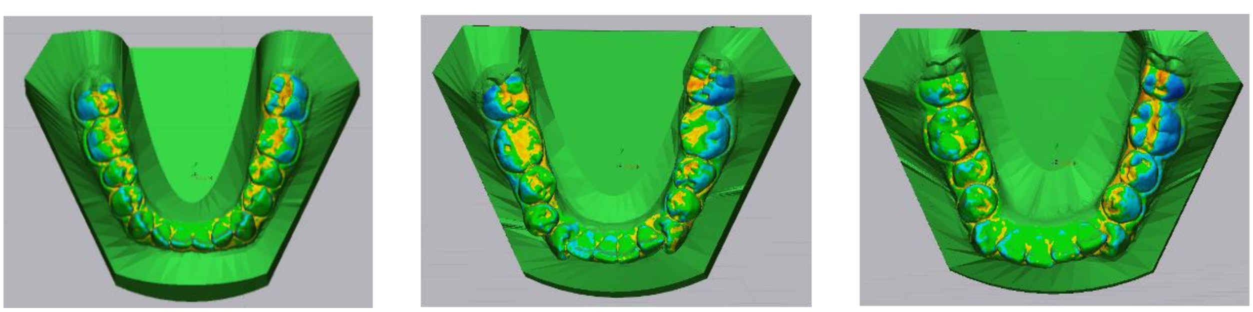

Figure 11. Sites commonly seen with discrepancies in 3D printed aligners. Buccal surfaces of posterior teeth displaying discrepancies, shown in blue.

Conclusions

1) The amount of crowding had no influence on the accuracy in both 3D printed and vacuum-formed aligners.

2) 3D printed aligners showed more precision and trueness to the original models compared to vacuum-formed aligners.

3) Both methods of fabrication are likely to be clinically acceptable with all levels of crowding present.

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