Optimizing 3D-Printed Orthodontic Models for Thermoformed Appliance Fabrication

2021 Grants

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FollowUp Form

Award Information

In an attempt to make things a little easier for the reviewer who will read this report, please consider these two questions before this is sent for review:

- *Is this an example of your very best work, in that it provides sufficient explanation and justification, and is something otherwise worthy of publication? (We do publish the Final Report on our website, so this does need to be complete and polished.)*
- *Does this Final Report provide the level of detail, etc. that you would expect, if you were the reviewer?*

Title of Project*

Optimizing 3D-Printed Orthodontic Models for Thermoformed Appliance Fabrication

Award Type

Biomedical Research Award (BRA)

Period of AAOF Support

July 1, 2021 through June 30, 2023

Institution

University of Texas at Houston

Names of principal advisor(s) / mentor(s), co-investigator(s) and consultant(s)

Dr. Jeryl D. English

Amount of Funding

$30,000.00

Abstract

(add specific directions for each type here)

Respond to the following questions:

Detailed results and inferences:*

If the work has been published, please attach a pdf of manuscript below by clicking "Upload a file".
OR
Use the text box below to describe in detail the results of your study. The intent is to share the knowledge you have generated with the AAOF and orthodontic community specifically and other who may benefit from your study. Table, Figures, Statistical Analysis, and interpretation of results should also be attached by clicking "Upload a file".

Table and Figures.pdf
Specific Aim 1 involved investigation of the effect of the material with which hollow 3D-printed models are made on the dimensional fidelity of appliances thermoformed upon the models. In order to remove the 3D printer model as a factor, all 5 investigated materials were 3D-printed using a single 3D printer model (Form 2, Formlabs, Inc.). Four materials marketed by Formlabs for use in dental model fabrication were investigated (Grey, Draft, and Model; https://dental.formlabs.com/materials/), as well as 2 engineering resins from Formlabs marketed for manufacturing applications (Grey Pro and Rigid 10K; https://formlabs.com/materials/engineering/). Ten models were fabricated from each material for each of 3 shell thicknesses (1.0 mm, 1.5 mm, and 2.0 mm) using the respective settings optimized by the manufacturer for use with the Form 2 model 3D printer. The surface of each model was scanned with an E3 Desktop Scanner (3Shape, Copenhagen, Denmark) before thermoforming an appliance and again after the release of the appliance. The intaglio surface of the thermoformed appliances was registered by a cast created with polyvinyl siloxane (PVS) impression material, which was scanned with the desktop scanner. For all model and appliance pairs (n=150), 3 types of scans (model before thermoforming [MB], model after thermoforming [MA], and PVS casting of the appliance [PVS]) were imported into metrology software (Geomagic Control X; 3D Systems, Rock Hill, SC) and analyzed to quantify dimensional deviations in terms of the percentage of the surface points within 0.25 mm bounds of acceptability (percent in-tolerance). The compressive mechanical properties of 3D-printed cylindrical samples (6 mm diameter, 12 mm height) of each material (n=10) were characterized in accordance with ASTM Standard D695. Dimensional deviation data and mechanical testing data were analyzed using generalized linear models in R statistical Software (R Core Team, Vienna, Austria, 2018).

Comparisons of the PVS casting of the intaglio surface of the thermoformed appliance with the model surface before thermoforming (MB-PVS) reflect the total deformation of the model during thermoforming (elastic and plastic deformation) imparted into the appliance. Accordingly, the MB-PVS comparison represents the dimensional accuracy of the appliance relative to the original model of the patient dentition, and it served as the comparison of primary interest in the context of this study. The models of 1.0 mm shell thickness fabricated with the Draft, Grey, Grey Pro, and Rigid 10K resins presented percent in-tolerance values ranging from 31.9 ± 7.9% to 88.5 ± 4.4% (Figures 1 and 2). The percent in-tolerance values increased for each resin as the shell thickness increased, with the 2.0 mm shell thickness models created from the Draft, Grey, and Grey Pro resins presenting in-tolerance values above 97%. The 2.0 mm shell thickness models created with the Rigid 10K material, however, presented a lower percent in-tolerance value of 93.9 ± 3.2%. The Rigid 10K models presented difficulty in release of the appliances after thermoforming, and the lower in-tolerance values for the thicker models of this material may reflect deformations imparted into the appliance as it was released. A statistically significant effect of material, shell thickness, and interaction effect of material and thickness was observed for the percent in-tolerance data from the MB-PVS comparison ($p<2.2\times10^{-16}$).

The peak compressive stress ranged from 75.1 ± 1.6 MPa to 80.5 ± 1.7 MPa for the Draft, Grey, Grey Pro, and Model materials, while it was statistically significantly higher at 275.0 ± 3.2 MPa for the Rigid 10K material (Table1; $p<0.001$). Similarly, the compressive modulus ranged from 1.6 ± 0.1 GPa to 1.7 ± 0.1 GPa for the Draft, Grey, Grey Pro, and Model materials, while it was statistically significantly higher at 3.9 ± 0.2 GPa for the Rigid 10K material ($p<0.001$). The mechanical testing data indicate significantly greater compressive mechanical properties of the Rigid 10K material relative to the other materials investigated. The data supports the observation of the difficulty of release of appliances from the Rigid 10K models, especially those of greater thicknesses, due to the stiffness of the material. The data also supports the greater percentage in-tolerance values observed for the 1.0 mm thickness Rigid 10K models compared to the other models and suggests that the Rigid 10K material presented sufficient strength to withstand the forces of thermoforming at thin shell thicknesses without significant deformation.

The data in Specific Aim 1 collectively support acceptance of the hypothesis that the model shell thickness affects the dimensional accuracy of thermoformed appliances, as indicated by the MB-PVS in-tolerance percentage values. The data also supports rejection of the hypothesis that the effect of model shell thickness is consistent across the materials investigated. The study demonstrates that materials with sufficient strength may withstand the forces of thermoforming without significant deformation, but that challenges in releasing the appliance may introduce undesired deviations in the appliance. Further, the study suggests that models of 2.0 mm shell thickness support the fabrication of appliances with the greatest dimensional accuracy under the conditions investigated.

Specific Aim 2 involved investigation of the effect of the 3D printer ecosystem and the shell thickness with which hollow 3D-printed models are made on the dimensional accuracy of appliances thermoformed upon the models. Models of 3 shell thickness (1.0 mm, 1.5 mm, and 2.0 mm) were printed using four 3D-printer ecosystems: Asiga UV, SprintRay Pro 95, Form 2, and Form 3B (n=10 per thickness per printer ecosystem) in strict compliance with the instructions for use of grey model resin materials validated for use in each respective ecosystem. As in Specific Aim 1, all models and appliance pairs (n=120) had 3 surface scans associated with each thickness: model before thermoforming [MB], model after thermoforming [MA], and a polyvinyl siloxane casting derived from the intaglio surface of the thermoformed appliance [PVS]. Scans were superimposed using a best-fit algorithm in metrology software (Geomagic Control X; 3D Systems, Rock Hill, SC) to yield 3 comparisons per model and appliance pair: MB-MA, MB-PVS, and MA-PVS in terms of the percentage of the surface points within 0.25 mm bounds of acceptability (percent in-tolerance). Dimensional deviation data were analyzed using generalized linear models in R statistical Software (R Core Team, Vienna, Austria, 2018).

Comparisons of the PVS casting of the intaglio surface of the thermoformed appliance with the model surface before thermoforming (MB-PVS) reflect the total deformation of the model during thermoforming (elastic and plastic deformation) imparted into the appliance. Accordingly, the MB-PVS comparison represents the dimensional accuracy of the appliance relative to the original model of the patient dentition, and it served as the comparison of primary interest in the context of Specific Aim 2. All models with shell thickness of 1.0 mm showed lower percent in-tolerance values when compared with shell thicknesses of 1.5 mm and 2.0 mm (Figures 3 and 4). Mean percent in-tolerance values for the printers at the 1.0 mm model shell thickness ranged from 34.83 ± 6.83 % for the Asiga printer to 77.75 ± 21.29% for the SprintRay printer. The average of the percentage in-tolerance values across all printers was approximately 59.1% at the 1.0 mm model shell thickness. At a model shell thickness of 1.5 mm, each printer demonstrated greater than 87% in-tolerance, with an average of approximately 91.1%. At a 2.0 mm model shell thickness, each printer demonstrated greater than 96% of data points in-tolerance, with an average of approximately 97.6%. At 1.5 mm model shell thickness, the Asiga printer presented the lowest mean in-tolerance value at 87.08 ± 14.29%. However, at a 2.0 mm model shell thickness, the Asiga printer presented the highest mean values at 98.25 ± 0.74% in-tolerance. The data suggests a trend of increasing in-tolerance values for each printer with increasing model shell thickness. A statistically significant effect of printer ecosystem (p<2.2×10^-16), shell thickness (p<2.2×10^-16), and interaction effect of printer ecosystem and thickness (p<2.2×10^-4) was observed for the percent in-tolerance data from the MB-PVS comparison.

The data from Specific Aim 2 collectively support rejection of the null hypothesis that the model shell thickness and 3D printer ecosystem do not affect the dimensional accuracy of thermoformed appliances, as indicated by the MB-PVS in-tolerance percentage values. The study demonstrates that the effects of model shell thickness and 3D printer ecosystem on the accuracy of thermoformed appliances presents complexity, as the effect of one variable is conditional upon the level of the other variable. Further, the study suggests that models with a minimum shell thickness of 2.0 mm should be used to minimize deformations when using the investigated 3D-printing ecosystems for the purpose of thermoforming appliances.

Were the original, specific aims of the proposal realized?*

Yes

Were the results published?*

Yes

Have the results of this proposal been presented?*

Yes

To what extent have you used, or how do you intend to use, AAOF funding to further your career?*

As a bioengineer, I am thrilled to explore exciting new frontiers at the intersection of engineering and orthodontics, and funding from the AAOF has been vital to enable my investigations in these areas that traditionally are not targets for funding from federal sources. The funding from AAOF provides me with opportunities to expand my exposure to the challenges of clinical orthodontics, to collaborate with clinicians and researchers in the field, to increase my research profile, and to broaden my professional network. Indeed, support from the AAOF has been instrumental in my career advancement through the academic ranks from an Assistant Professor to Professor (Tenured). The benefits enabled by AAOF support provide a firm foundation upon which I plan to continue to build my research program in topics of relevance to orthodontics.

Comment: *We commend your accomplishments, Dr. Kasper and encourage you to continue the cross-cutting research that you contribute from an engineering perspective.*

Accounting: Were there any leftover funds?

$2,186.29

Published

Citations*

You indicated results have been published. Please list the cited reference/s for publication/s including titles, dates, author or co-authors, journal, issue and page numbers

Mount, J. (2022). Effect of 3D-printed model material on thermoformed appliance fabrication (Order No. 29069027). Available from Dissertations & Theses @ University of Texas School of Dentistry at Houston. (2652612848). Retrieved from https://uthdentistry.idm.oclc.org/login?url=https://www.proquest.com/dissertations-theses/effect-3d-printed-model-material-on-thermoformed/docview/2652612848/se-2

The project involved contributions from 2 residents in partial completion of the requirements of the degree of Masters of Science in Dentistry. Some project results were published in a thesis detailed above and other results will be published in a planned thesis, as follows:

Nguyen, C. D. Shear bond strength of orthodontic brackets fabricated via 3D-printing using filled biocompatible resins. Masters of Science in Dentistry Thesis, Department of Orthodontics, The University of Texas School of Dentistry at Houston, Houston, Texas. (in preparation).

In addition, two research manuscripts based on the results of the project are presently under preparation for submission to peer-reviewed journals. In each case, the submissions will acknowledge AAOF support, as appropriate.

Was AAOF support acknowledged?

If so, please describe:

Yes, as appropriate, AAOF support was acknowledged in each publication.

Presented

Please list titles, author or co-authors of these presentation/s, year and locations:*

1. “Leaving the Stone Age: Applying 3D Printing to Meet Clinical Needs in Oral Health Care,” Capital Area Dental Society, Balcones Country Club, Austin, Texas (June 20, 2023) With Kasper FK*.

2. “Current and Emerging Applications of 3D Printing in Orthodontics,” 2023 Annual Session of the American Association of Orthodontists, Chicago, Illinois (April 21-24, 2023) With Kasper FK*.

3. “Leaving the Stone Age: Applying 3D Printing to Meet Clinical Needs in Oral Healthcare,” Greater Houston Dental Hygienists’ Association, Patterson Dental, Houston, Texas. (February 7, 2023) With Kasper FK*.

4. “Next Generation 3D Printing Materials & Technologies,” 9th Biennial Meeting of the Consortium for Orthodontic Advances in Science and Technology (COAST), Lake Arrowhead, California. (November 9, 2022) With Kasper FK*.

5. “Leaving the Stone Age: Applying Biomaterials and 3D Printing to Meet Clinical Needs,” 79th Annual Meeting of the American Institute of Oral Biology, Palm Springs, California. (October 22, 2022) With Kasper FK*.

6. “Evolving Biomaterial-based Approaches for Craniofacial Bone Regeneration,” 79th Annual Meeting of the American Institute of Oral Biology, Palm Springs, California. (October 21, 2022) With Kasper FK*.

7. “Current and Emerging Applications of 3D Printing in Orthodontics,” Oregon Health & Sciences University Orthodontic Alumni Association, 2022 Hixon Memorial Lecture, Portland, Oregon. (September 9, 2022) With Kasper FK*.

Comment: *This is an impressive list of your contributions, and we look forward to seeing more of your work in the future.*

Was AAOF support acknowledged?

If so, please describe:

Yes, as appropriate, AAOF support was acknowledged in each presentation.

Internal Review

Reviewer Comments

Reviewer Status*

Approved

File Attachment Summary

Applicant File Uploads

- Table and Figures.pdf

Table 1: Peak Compressive Stress & Compressive Modulus (Mean ± Standard Deviation)

	DraftV1	Grey V2	GreyPro V1	Model V2	Rigid 10K	P
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	
Peak Compressive Stress (MPa)	75.14 ± 1.57	77.26 ± 1.39	80.50 ± 1.70	76.61 ± 2.41	274.96 ± 3.17	< 0.0001*
Compressive Modulus (MPa)	1.56 ± 0.10	1.68 ± 0.46	1.73 ± 0.06	1.66 ± 0.06	3.95 ± 0.22	< 0.0001*

Figure 1: Line plots representing percent in-tolerance values for MB-PVS comparisons. Data points represent means with the associated 95% confidence intervals. Thicknesses of 10, 15, and 20 indicate shell thicknesses of 1.0, 1.5, and 2.0 mm, respectively. X-axis displays materials used in the study. Y-axis displays proportion in-tolerance.

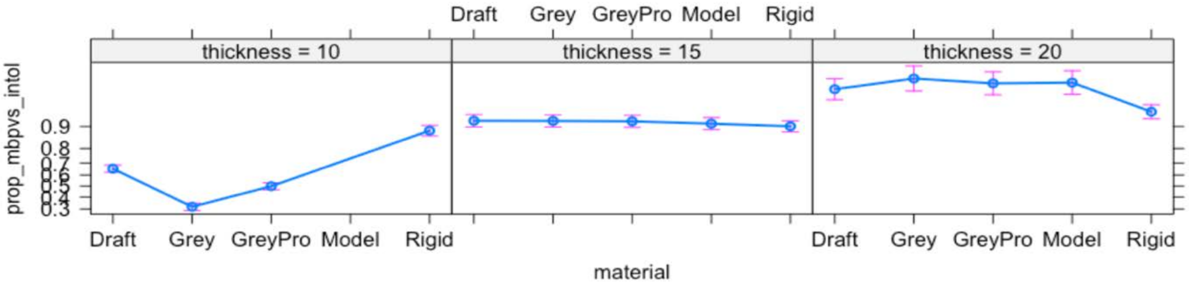

Figure 2: Representative superimpositions show deviations between the PVS casting derived from the intaglio surface of thermoformed appliances and paired Model Before thermoforming (MB-PVS) for each shell thickness and each material. Green represents areas within tolerance (±0.250 mm); red represents areas of positive deviation greater than +0.250 mm; and, blue represents areas of negative deviation greater than 0.250 mm in magnitude. Deviations indicate elastic and plastic deformation of the model imparted into the thermoformed appliance. Light blue colors represent mismatch between models at the digitally trimmed margins.

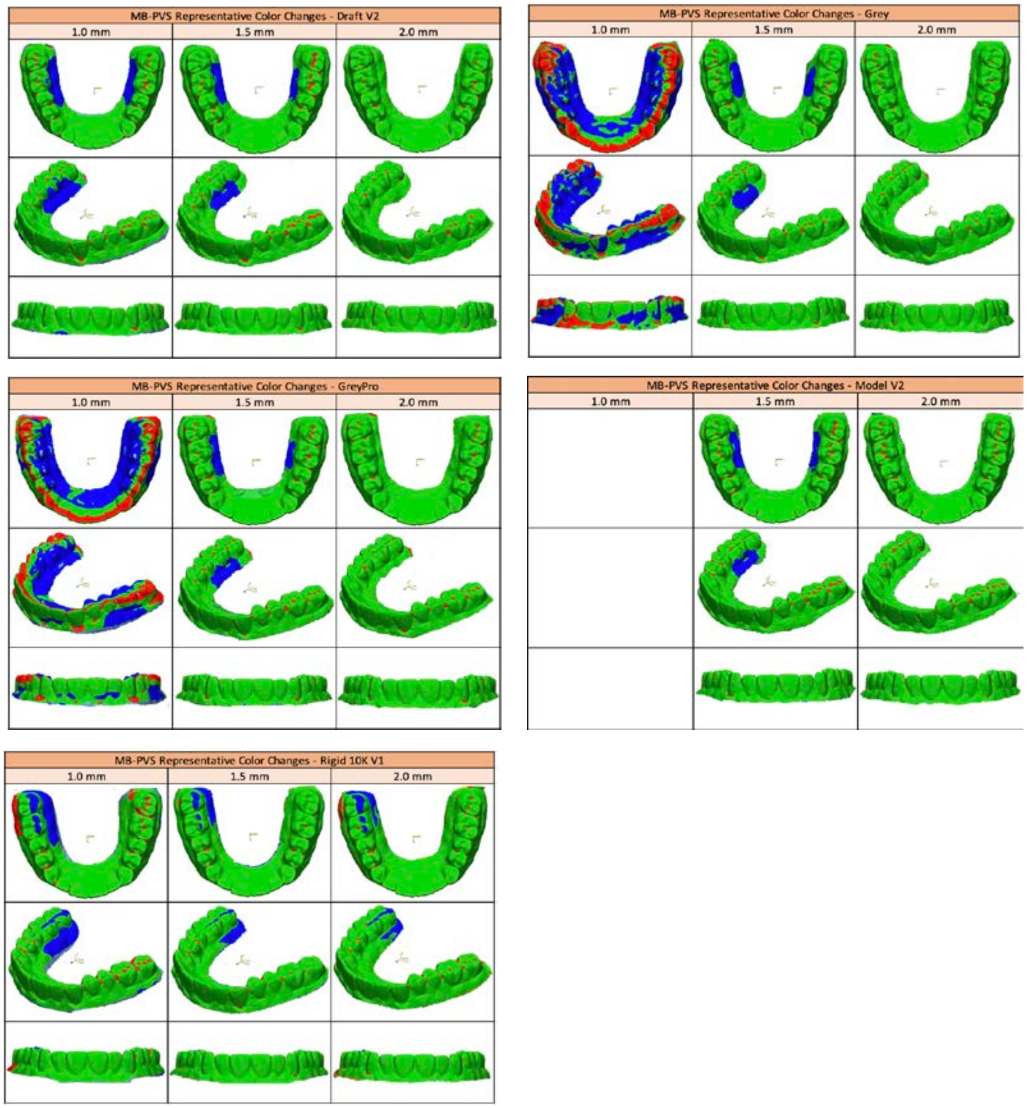

Figure 3. Line plots representing percent in-tolerance values for MB-PVS comparisons. Data points represent means with the associated 95% confidence intervals. Thicknesses of 10, 15, and 20 indicate shell thicknesses of 1.0, 1.5, and 2.0 mm, respectively. X-axis displays 3D-printers used in the study. Y-axis displays proportion in-tolerance.

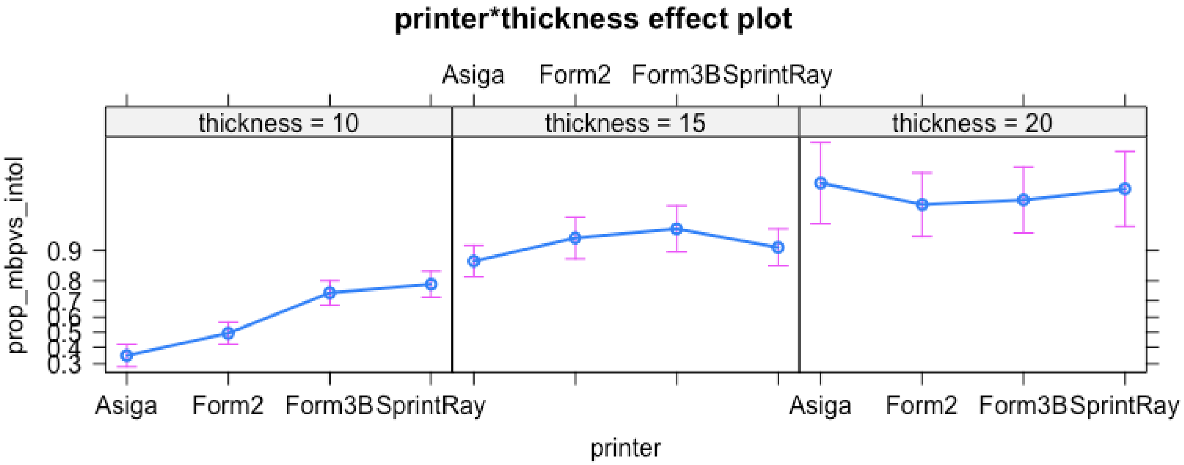

Figure 4. Representative superimpositions show deviations between the PVS casting derived from the intaglio surface of thermoformed appliances and paired Model Before thermoforming (MB-PVS) for each shell thickness and each 3D-printer ecosystem. Green represents areas within tolerance (±0.250 mm); red represents areas of positive deviation greater than +0.250 mm; and, blue represents areas of negative deviation greater than 0.250 mm in magnitude. Deviations indicate elastic and plastic deformation of the model imparted into the thermoformed appliance. Light blue colors represent mismatch between models at the digitally trimmed margins.