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Deflection Values As A Result Of Thermoforming Of 3D-Printed Dental Models Of Varying Wall Thicknesses During Clear Aligner Fabrication: 3D Deformation Analysis

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Abstract
Introduction: *Clear aligner fabrication demands a very high level of accuracy. Thermoforming is done at aheavy pressure of 4-6 bars; which makes the 3D-printed dental models easily prone to deformation. This study employs three-dimensional printed models with varying wall thicknesses to investigate how these variations impact their resistance to deformation during aligner fabrication.*
Aims & Objectives: *The primary objective of the study was to analyzedeformation as a result of thermoforming of 3D-printed dental models of varying wall thicknesses.*
Material & Methods: *A total of hundred models of varying wall thicknesses (10 each of 1.0mm,1.25mm, 1.5mm,1.75 mm, 2.0mm,2.25mm, 2.5mm, 2.75mm, 3.0mm and solid) were printed using a MSLA 3D Printer (Saturn 3 12K, Elegoo, Shenzhen, China) using model resin (Elegoo Standard LCD Light-curing UV resin, Shenzhen, China).Printing was followed by cleaning and curing of the models according to the manufacturers' guidelines. Aligners when then fabricated using Bio Star (Scheu Dental, Iserlohn, Germany) utilizing a 30sec cycle for a 0.8mm aligner sheet (Erkodent-AL, Erkodur, Pfalzgrafenweiler, Germany). Each model was then scanned with a lab scanner (T710, Medit Corp., Seoul, South Korea) and compared with the original 3D model using 3D comparison software (CloudCompare v2.13.1, Santry, Dublin, Ireland) and results were quantified.*
Results: *Models with 1mm and 1.25mm showed visible deformation, hence were not considered for deformation analysis. The average post deformation accuracy ranged from 83.529% for 1.50mm thick models to 99.1495% for solid models.The results show that model with wall thickness of 2.75mm or greater showed negligible deformation and can be used for clear aligner fabrication.*
Conclusion: *Hollow models with a shell thickness exceeding 2.75 mm are suggested for aligner production due to their ability to withstand stresses during thermoforming, while using less resin per unit compared to solid models. This approach,also offers cost savings, time efficiency, and environmental benefits, making it a more viable option for aligner fabrication.*
Keywords: *Clear aligner fabrication, Thermoforming3D-printed dental models, Deformation resistance, MSLA 3D Printer, Model resin, Bio Star, 3D comparison software, Accuracy, Shell thickness, Cost savings, Environmental benefits*

INTRODUCTION

The field of Orthodontics has developed significantly through the times, with numerous advances in part due to digital dentistry. One common illustration is the shift down from physical impressions toward intra oral scanners, which patients find more comfortable[1].The new technology to scan a dental arch has led to several enhancements making digital workflow seamless, in turn increasing the usability of aligner therapy.The direct

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3D printing of clear aligners represents a significant leap forward, promising substantial improvements in customization and turnaround time for orthodontic treatments.[2]

Clear aligners have transformedthe landscape of Orthodontic treatment, offering patients a discreet, convenient, and effective alternative to traditional braces. This innovative Orthodontic appliance consist of transparent, custom-fit trays that gently and gradually shift teeth into proper alignment over time. This aesthetic advantage not only enhances the patient's confidence during treatment but also minimizes the impact on their daily appearance and social interactions[3,4].

In addition to their aesthetic benefits, clear aligners provide unmatched convenience due to their removable nature. Unlike traditional braces, which are fixed in place for the duration of treatment, clear aligners can be taken out for eating, drinking, brushing, and flossing. Understanding the economic implications of adopting 3D printed clear aligners is crucial as this technology reshapes the cost structure of orthodontic practices.[5]

This makes it easier for patients to maintain good oral hygiene throughout their Orthodontic journey, reducing the risk of dental issues such as decay and gum disease. The ability to remove aligners also allows patients to enjoy a wider variety of foods without restrictions, which is a significant lifestyle advantage over traditional braces.[6]

The predictability and precision of clear aligner treatment are further enhanced by the ability to monitor progress digitally. Patients can see virtual representations of their treatment plan and how their teeth will gradually shift into alignment over time[7]. This digital monitoring allows Orthodontists to make any necessary adjustments to the treatment plan as needed, ensuring optimal outcomes with minimal discomfort and inconvenience for the patient.Recent advancements in 3D printing technologies have revolutionized the creation of dental prostheses.[8]

To minimize cost and materials requisite, models can be 3D printed with a hollow geometry of varying wall thickness in comparison to the conventional solid fabrication. Although there are numerous positive associations with printing hollow models, the models still need to be strong enough to have the ability to tolerate the thermoforming step to fabricate clinically permissible aligners.[9]

This research enabled us to recognize the appropriate wall thickness of hollow models, which will allow us to discern optimal material usage with minimal deformation.

Aims & Objectives

The primary objective of the study was to evaluate deformation as a result of thermoforming of 3D-printed dental models of varying wall thicknesses (1mm, 1.25 mm, 1.50mm, 1.75mm, 2.0mm, 2.25mm, 2.50mm and 2.75mm) and compare it to solid 3D models.

MATERIALS & METHODS

The maxillary arch of a patient was scanned with an intraoral scanner (Virtuo Vivo, Straumann Corp., Basel, Switzerland). Scanning strategy **(Fig. 1)**used for all the scans was as follows:

Step	Surface	Direction	Additional Notes
1.	Left Occlusal Surface	Posterior to anterior	Start from the back teeth, move forward
2.	Anterior teeth	Canine to canine (zig-zag)	Use a zig- zag motion for better coverage
3.	Right occlusal surface	Posterior to anterior	Start from the back teeth, move forward
4.	Palatal/ Lingual surface	Right to left	Cover the inner surface of the teeth
5.	Left buccal surface	Posterior to anterior	Scan the outer surface, moving forward

6.	Right buccal surface	Posterior to anterior	Scan the outer surface, moving forward

Table 1: Scanning strategy

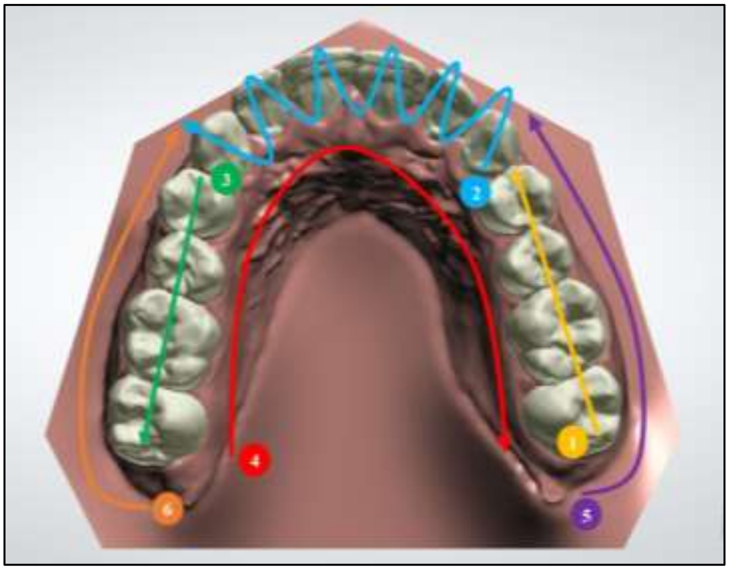

Figure 1: Scanning strategy

The STL file was then converted into a 3D model capable of being printed using design software (Meshmixer v3.5, Autodesk, San Francisco, California, USofA)**(Fig. 2)**. A solid model along with hollow models of varying thicknesses: 1mm, 1.25mm, 1.50mm, 1.75mm, 2.0mm, 2.25mm, 2.50mm and 2.75mm were prepared **(Fig. 3)**and arranged for printing using orientation software (Chitubox v1.9.5, CBD Technology, China) **(Fig. 4)**.Five models were positioned horizontally for printing with the occlusal plane facing upwards andsupports were added for stability during printing.

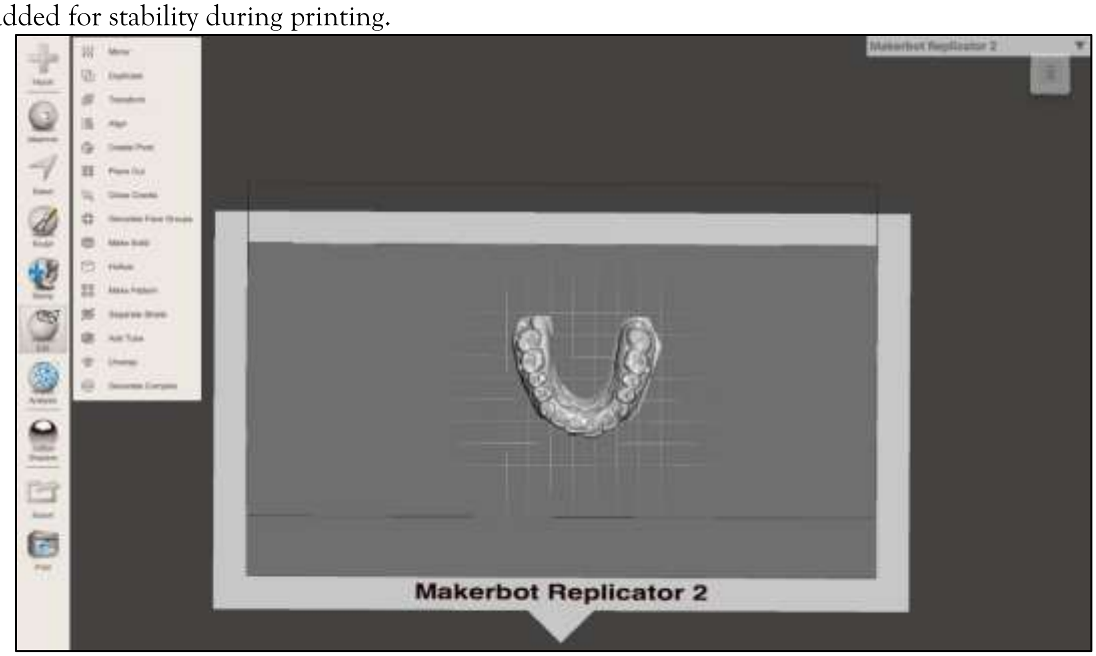

Figure 2: Meshmixer v3.5 interface

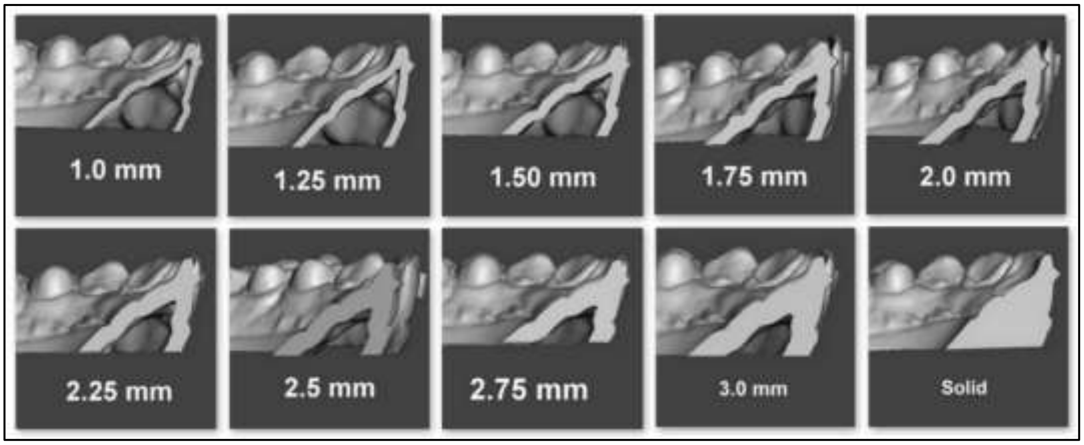

Figure 3: 3D Models of varying wall thicknesses

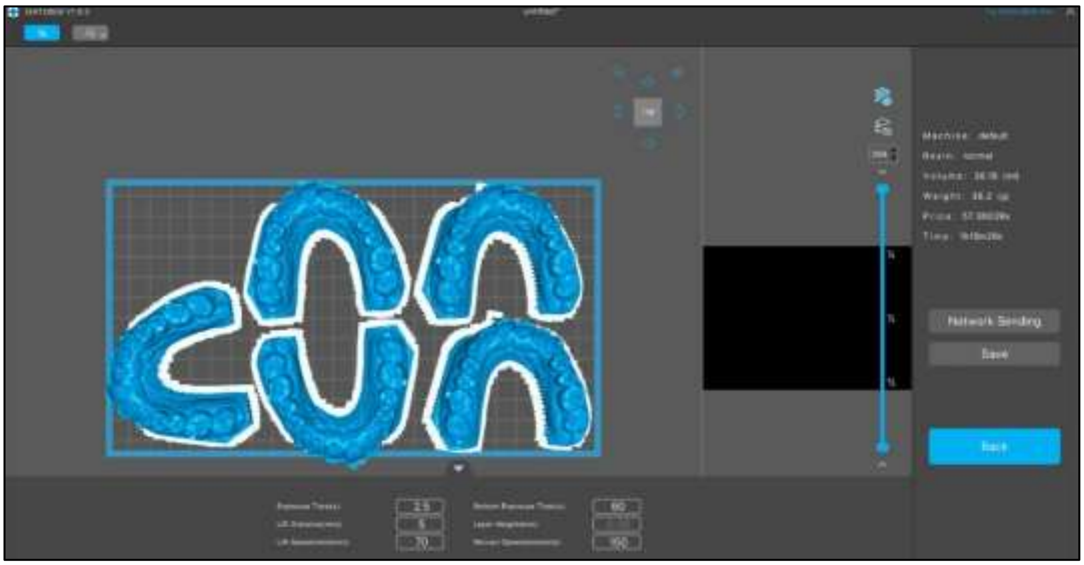

Figure 4: Chitubox v1.9.5 interface

Hundredmodels were printed in total, 10 of each wall thickness (1mm, 1.25mm, 1.50mm, 1.75mm, 2.0mm, 2.25mm, 2.50mm, 2.75mm and solid model) using a MSLA 3D printer (Elegoo Saturn 3 12K, Shenzhen, China). Propriety model resin (Standard LCD light curing UV resin, Elegoo, Shenzhen, China) was used for printing of all aforementioned models.

Post processing of 3D models which included scrapping of models from the model build plate, models were then rinsed in 99% isopropyl alcohol (IPA) in ultrasonic cleaning unit for 1.5 minutes to remove excess uncured resin. After cleaning, the modelswere dried, using compressed air. The cleaned model when then cured under UV light to harden the resin fully. This wasdone using a UV curing unit for 15 minutes according to the manufacturers' guidelines. The models were ready for aligner fabrication.

Aligners were then fabricated using a thermoforming machine (Bio Star, Scheu Dental, Iserlohn, Germany)utilizing a 30sec cycle for a 0.8mm aligner sheet (Erkodent-AL, Erkodur, Pfalzgrafenweiler, Germany) (**Fig. 5**).

Figure 5: 0.8mm aligner sheet (Erkodent-AL)

Models subjected to visible and devastating compression during thermoforming were not subjected to analysis (1mm, 1.25mm) **(Fig. 6)**. All other aligners were removed from 3D-printed models and each model was scanned using a lab scanner (T710, Medit Corp., Seoul, South Korea)**(Fig. 7)**.

Figure 6: 1.25mm model showing visible deformation after thermoforming

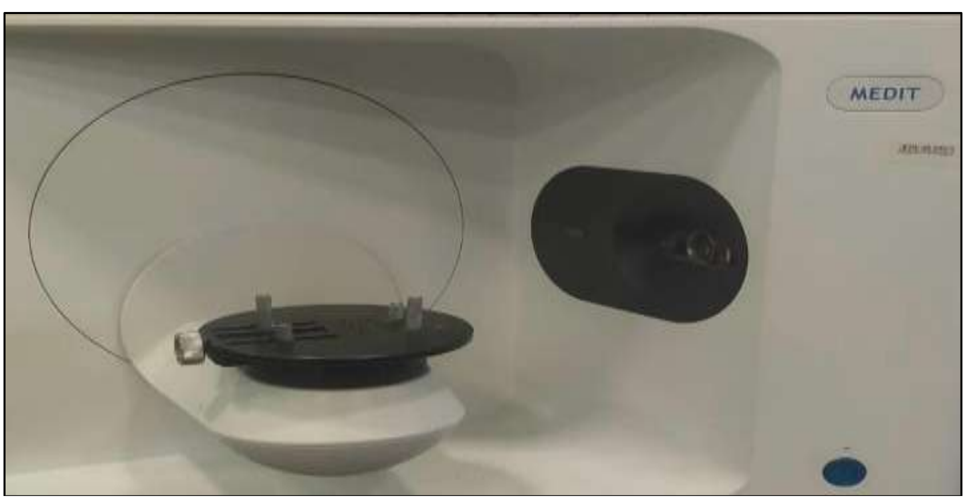

Figure 7: Lab scanner (T710, Medit Corp.)

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The files were then compared to the original 3D model using 3D comparison software (Cloud Compare V2.13.1, Santry, Dublin, Ireland) and results were quantified and colour deviation maps were generated for each scanned models.

RESULTS

A total of eighty models from hundred models were evaluated. Several models of thinner wall (1mm, 1.25mm) did not survive thermoforming and showed visible deformation, hence were not subjected to 3D deformation analysis. The individual percentage of tolerance of each model with wall thickness is tabulated(**Table 2**).

The average percentage of tolerance is tabulated in Table 3. This trend suggests that the additional wall thickness provides more stability and support, resulting lesser deformation after thermoforming, and in term higher accuracy of aligner fabricated

	1.5mm	**1.75mm**	**2.0mm**	**2.25mm**	**2.50mm**	**2.75mm**	**3.0mm**	**Solid**
Model 1	84.12	86.19	87.27	90.29	95.78	97.5	99.0	97.86
Model 2	83.88	87.32	88.56	92.15	96.32	99	98.5	98.23
Model 3	85.59	88.57	90.01	93.84	97.14	98.8	99.5	98.74
Model 4	77.47	89.01	91.23	95.22	97.89	97.3	98.0	99.02
Model 5	84.32	89.46	90.89	94.67	98.22	99.2	99.1	99.31
Model 6	85.12	90.12	89.75	91.98	98.41	98.6	98.9	99.45
Model 7	83.76	89.88	91.45	94.36	97.66	98.9	98.7	99.18
Model 8	84.91	88.76	92.19	93.71	97.98	98.1	98.4	99.55
Model 9	82.99	87.94	88.92	94.89	98.12	99.5	99.2	98.97
Model 10	83.61	90.36	92.46	95.56	98.53	97.	98.6	98.66
Mean values	83.5329	86.7781	88.8694	93.5673	97.4932	98.7214	98.976	99.1495

Table 2: Analysis of 10 models of various wall thickness showing accuracy percentage

Thickness of Model	**Number of Models**	**Average Accuracy percentage**	**Average Deformation percentage**	**Minimum Accuracy**	**Maximum Accuracy**
1.50mm	10	83.5329	16.467	77.47	85.59
1.75mm	10	86.7781	13.2219	86.19	90.36
2.0mm	10	88.8694	11.1306	87.27	92.46
2.25mm	10	93.5673	6.4327	90.29	95.56
2.50mm	10	97.4932	2.5068	95.78	98.53
2.75mm	10	98.7214	1.2786	97.3	99.2
3.0mm	10	98.976	1.024	98.0	99.5
Solid	10	99.1495	0.8505	97.86	99.55

Table 3: The descriptive statistics table demonstrate the data of each group studied

With reference of the results, it was observed that with increase in thickness, there is an increase in accuracy of models even after thermoforming.Color deviation maps were generated for each scanned models. The dark blue color indicates negative deviations greater than 0.3 mm, and green areas indicate deviations less than 0.3 mm, which lie within the limits of clinical acceptability **(Fig. 8)**.

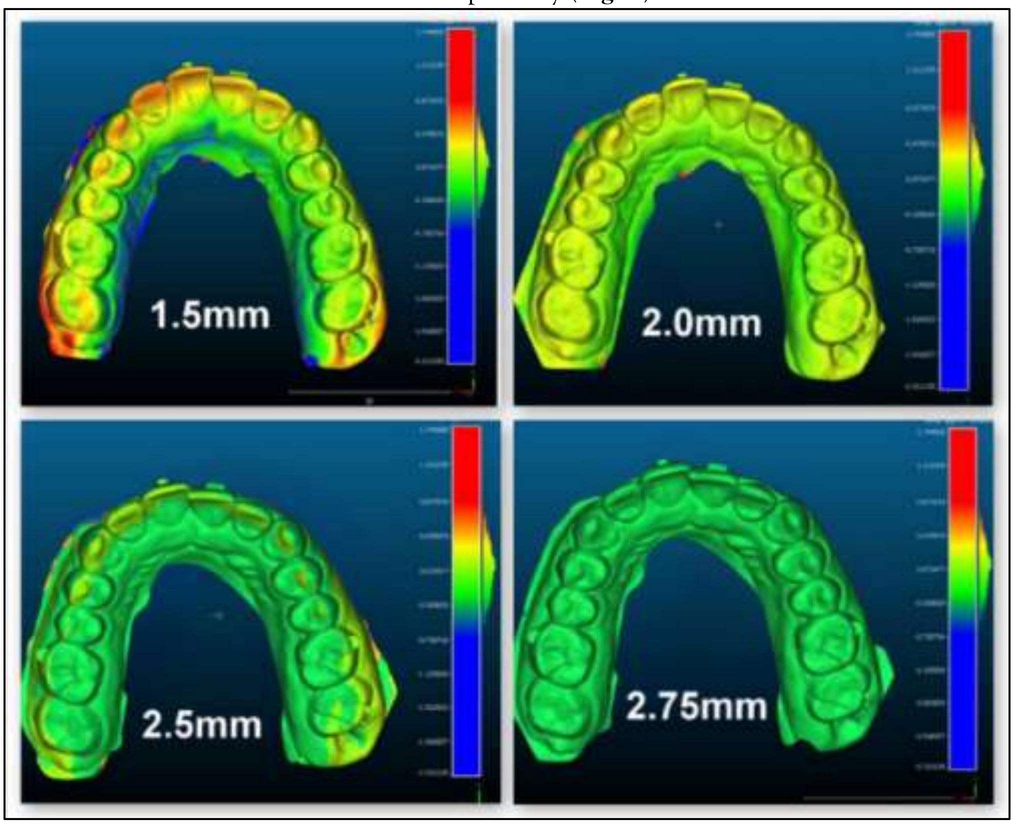

Figure 8: 3D Deformation analysis

The 1.5mm group was significantly deformed compared to solid, whereas 2.50mm group was not significantly different from solid.Accuracy of models after thermoforming was as observed**(Fig. 9)**.

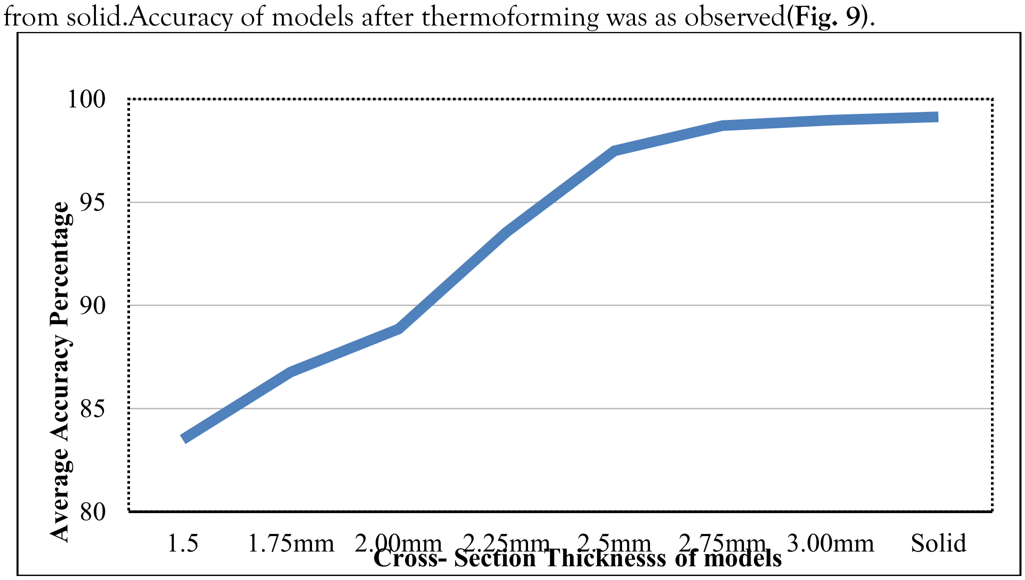

Fig. 9: Average Accuracy Percentage VsCross-Section Thickness of models

DISCUSSION

The objective of this research was to investigate whether there is a difference in the accuracy of thermoformed in-office clear aligners between 3D-printed hollow models and solid models, and to determine the minimum shell thickness required to manufacture aligners that meet clinical standards and can endure thermoforming. According to the findings, noticeable distortions were observed in models printed with less than 2.75 mm of thickness. Consequently, we rejected the null hypothesis that all model thicknesses yield comparable dimensional accuracy when thermoformed for orthodontic applications.

Several of the 1.0 mm models could not be removed from their supports without fracturing, and those that did, were subject to considerable plastic deformation. Additionally, some plastic deformation was observed in the 1.25 mm models after aligner thermoforming.

Advancements in intraoral digital scanning and 3D modeling technologies have significantly enhanced the accuracy and effectiveness of clear aligner treatments.[10] Before treatment begins, Orthodontists use intraoral scanners to create precise 3D digital models of the patient's teeth and bite. These digital models are utilized to design the complete treatment plan, forecasting the movement of each tooth during the process. The aligners are custom-made based on these digital models, ensuring that each tray applies the right amount of pressure to specific teeth at precise intervals to achieve the desired results. This degree of accuracy enhances treatment efficiency while minimizing the need for frequent adjustments usually necessary with conventional braces. Digital scans have verified to be able to capture the surface detail of a patient's mouth with an equivalent degree of accuracy (within a 0.10mm overall deviation) as compared with alginate impressions[3]

The increase in availability and advancements in technology has led to the number of patients' receiving clear aligner therapy growing annually[4,11].With this enhancement in the field, there has been trials with in-office fabrication of clear aligners. In-office fabrication of clear aligners comes with significant profitable benefits, but little is known about the most efficient and effective assembly methods for models[5].

In a related study examining the dimensional accuracy of appliances created from hollow models, researchers sought to evaluate how the wall thickness of 3D-printed models affects the precision of pressure-formed clear aligners.[12] Their findings differed from our own, that a thickness of 2.0 mm is the minimum required to produce aligners that meet clinical standards[13]. According to their data, hollow models with a 2.0 mm thickness yield aligners that are clinically acceptable against our findings of 2.75 mm. The variation is possible because of change in resin material and it's properties.

The shift towards hollow printing represents a significant advancement in reducing material waste and print times in 3D printing.[14] However, ongoing research is now exploring the potential to entirely eliminate the requirement for printing 3D models in aligner fabrication. This suggests a future where clear aligners could be directly printed without the need for intermediary dental models. TC-85DAC resin, branded as Graphy, marked a breakthrough as the first directly printed aligner material, paving the way for other companies to introduce their own aligner resins [15].

Our understanding of directly 3D printed aligners is currently in the early stages.[16] According to a recent study doneby Can et al. (2022)[17], which examined TC-85DAC resin aligners, they showed no signs of wear or deterioration after one week of use. This suggests promising durability for these newly developed aligners. As the materials for directly printing aligners continue to advance, their current reliability remains a concern.[18] Therefore, exploring alternative approaches, such as printing models with hollow designs to minimize material usage, becomes essential. Understanding the limitations of direct printing is crucial, particularly regarding its potential impact on the precision of tooth movement during orthodontic treatment. This awareness underscores the need to rely on established knowledge and sustainable practices in 3D printing to navigate these challenges effectively.

By leveraging existing research and technological advancements, orthodontic practitioners can mitigate risks associated with early-stage materials and ensure consistent treatment outcomes.[19] The ability to maintain precise control over tooth alignment and occlusion is paramount in achieving successful orthodontic results. Therefore, while direct printing of aligners holds promise for future advancements in dental care, current practices should integrate cautious consideration of material limitations and operational constraints.

While the field of 3D printing in Orthodontics evolves, strategic use of hollow models and other waste-reducing techniques can optimize efficiency and reliability in aligner fabrication.[20] This approach not only addresses current material challenges but also paves the way for future innovations that enhance clinical precision and patient care in orthodontics.

In summary, the study emphasizes the importance of selecting an appropriate wall thickness in 3D printed models for thermoforming applications, where thicker walls contribute significantly to maintaining structural integrity and ensuring accurate reproduction of dental aligners or similar products.[21]These models proved particularly beneficial in contexts prioritizing durability and reliability, such as dental education and patient education settings. Optimal wall thicknesses for bulk printing were identified within the 2mm to 3mm range, balancing resin efficiency with dimensional stability to maximize cost-effectiveness without compromising quality[22].These findings are crucial for optimizing manufacturing processes and achieving consistent quality in orthodontic applications utilizing 3D printing technologies.

Limitation of the study

Limitation of this study is its focus on deformation of 3D-printed dental models with varying wall thicknesses when exposed to thermoforming pressures typical for clear aligner fabrication. The study's reliance on a specific brand and type of resin, as well as a particular 3D printing technology (MSLA), may limit the generalizability of the findings to other types of resins or different 3D printing technologies. Additionally, the study did not consider the potential variability in resin properties over time or with different storage conditions, which could influence the outcomes of thermoforming. Furthermore, the environmental conditions under which printing and thermoforming were conducted were not controlled or varied, which might affect the reproducibility of the results in different clinical and laboratory settings. Finally, while the study provides valuable insights into the optimal thickness for reducing deformation, it does not explore the long-term durability of the printed models under repeated use, which is critical for their practical application in orthodontics.

CONCLUSION

The precision of thermoformed aligners, which are crafted from 3D-printed dental models, is intricately tied to their wall thickness. A critical consideration in this process is ensuring that the wall thicknesses of these 3D models is sufficient to maintain structural integrity throughout both the printing and thermoforming stages. If the wall thickness is too thin, it risks compromising the stability of the 3D-printed model, leading to potential inaccuracies in the final product and ultimately ineffective Orthodontic corrections. Our research deepens the importance of this parameter in achieving reliable treatment outcomes.Based on our findings, we recommend that clinicians who produce in-office aligners opt for hollow models with a shell thickness of 2.75mm. This approach offers several advantages. Firstly, a thicker shell enhances the robustness of the 3D printed models, reducing the likelihood of structural issues during printing and thermoforming. This, in turn, enhances the accuracy and consistency of the aligners produced, ensuring that they effectively guide tooth movement as intended.

Furthermore, using hollow models with a 2.75 mm shell thickness can lead improves printing efficiency by optimizing material usage and reducing print times. This efficiency not only streamlines the production process but also contributes to cost savings associated with materials and operational expenses. Additionally, minimizing material wastage aligns with eco-friendly practices, promoting sustainability within dental practices.Selecting an appropriate shell thickness for 3D-printed dental models is pivotal in achieving precise thermoformed aligners for orthodontic treatment.

Clinicians are encouraged to adopt our recommended approach of employing hollow models with a 2.75 mm shell thickness to enhance reliability, efficiency, and sustainability in aligner fabrication within their practice settings. This strategy not only supports effective orthodontic care but also aligns with responsible resource management in modern dental workflows.

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