(International Print/Online Journal)

SJIF IMPACT FACTOR: 6.829
PUBMED-National Library of Medicine ID-101739732

ISSN (Print): 2209-2870
ISSN (Online): 2209-2862

International Journal of Medical Science and Current Research (IJMSCR)
Available online at: www.ijmscr.com
Volume 8, Issue 5 , Page No: 175-185
September-October 2025

IJMSCR

Undercut Dialemma – Decoding Aligner Thickness And Treatment Success

***Bandela Anand Babu[1], Puvvula Navya[2], Vizia Muddada[3], Payal Jyothi dash[4], Mahulkar Niharika[5] , Limasunep Jamir[6], Gali Udayadityeswari[6], Pentapalli Prasanthi[7]**

[1]Postgraduate, [2]Professor and HOD, [3]Professor, [4]Assistant Professor, [5]Postgraduate, [6]Assistant Pofessor, [7]Postgraduate. Deparment of Orthodontics & Dentofacial Orthopedics,Sree Sai Dental College And Research Institute, Srikakulam, Andhrapradesh.

***Corresponding Author:**
Bandela Anand Babu
Postgradute, Deparment of Orthodontics & Dentofacial Orthopedics, Sree Sai Dental College And Research Institute, Srikakulam, Andhrapradesh.

Type of Publication: Original Research Paper
Conflicts of Interest: Nil

Abstract

Aim:
To investigate how the presence of dental undercuts affects the final thickness of clear aligners after thermoforming, using models with varying maxillary incisor angulations.

Materials and Methods:
Twenty thermoformed clear aligners (0.8 mm Erkodur-Al sheets) were fabricated over four identical 3D printed resin models of a single patient, each modified to present different incisor angulations: 90°, 100°, 110°, and 120°. Five aligners were formed on each model. Post-thermoforming, aligner thickness was measured at the cervical regions of tooth 11 (anterior) and tooth 16 (posterior) using a digital vernier caliper. Data were analyzed using Kruskal-Wallis and Mann-Whitney U tests.

Results:
Significant thinning of aligners was observed at tooth 11 with increasing angulation ($p = 0.001$), with thickness decreasing from 0.62 mm (90°) to 0.24 mm (120°). In contrast, variations in thickness at tooth 16 were not statistically significant ($p = 0.222$). A significant inter-tooth difference was noted at 120°, where tooth 11 exhibited substantially thinner aligners than tooth 16 ($p = 0.007$).

Conclusion:
Incisal proclination and associated undercuts significantly affect the final thickness of clear aligners, particularly in the anterior region. Thinner aligners in these areas may compromise force delivery and treatment predictability. These findings underscore the importance of accounting for anatomical undercuts in aligner design and fabrication to enhance clinical outcomes.

Keywords: Clear aligners, Orthodontics, Thermoforming, Invisible Orthodontics

Introduction

Over recent decades, modern orthodontics has advanced significantly due to the development of new materials and techniques. Aesthetic considerations have driven much of this progress, leading to increased demand for orthodontic treatment across all age groups. Clear aligner therapy (CAT), which offers a visually discreet alternative to traditional braces for treating mild malocclusions, has gained widespread popularity among both patients and clinicians due to its comfort, reduced pain, improved oral hygiene, and overall effectiveness.

The foundation of aligner technology dates back to 1945, when Kesling introduced a pioneering method using plastic-based aligners for minor tooth movements[1]. The advent of computer-aided design and manufacturing (CAD/CAM) revolutionized orthodontics, culminating in the introduction of Invisalign® by Align Technology in the late 20th century—the first digitally produced clear aligner system.

Modern dental practices increasingly utilize 3D printing integrated with CAD/CAM, which involves three main stages: digitization, design, and fabrication. This technology offers notable benefits such as fast production, high precision, and enhanced patient comfort.[2]

The effectiveness of CAT depends on various factors including tooth morphology, type of movement, attachment configuration, aligner thickness, and both patient- and clinician-related variables. According to research and manufacturer data, clear aligners can range in thickness from 0.5 mm to 1.5 mm. Additional design elements such as the height of the aligner margins (ranging from 0 to 4 mm from the gingival zenith) and margin shapes (either scalloped or straight) may significantly influence aligner fit, force transmission, and the efficiency of orthodontic tooth movement.[3]

Modern orthodontics primarily aims to offer patients treatments that are both comfortable and satisfying, ultimately contributing to an improved quality of life. However, any pain or discomfort experienced during orthodontic procedures can have a negative impact on this overall well-being. Among the various factors influencing the success of clear aligner therapy (CAT), patient cooperation stands out as the most crucial. To better understand patient expectations and goals, and to assist clinicians in tailoring treatment accordingly, the use of questionnaires can be particularly valuable for improving treatment outcomes.

A substantial number of studies have examined the differences in treatment outcomes, patient satisfaction, and quality of life between those undergoing treatment with clear aligners and those using fixed appliances. The majority of these investigations have concluded that patient satisfaction is generally higher with CAT compared to traditional fixed orthodontic options. Despite this, there is still a lack of comprehensive studies that directly compare the different types of aligner systems and materials used in CAT.

While numerous studies have evaluated tooth movement as well as the biomechanical and clinical implications of various aligner features—particularly focusing on the shape and positioning of attachments—research specifically analyzing the impact of aligner thickness remains scarce. Some studies have utilized in-house clear aligner systems to explore these variables; however, the existing body of research is largely composed of non-randomized controlled trials, retrospective analyses, case reports, finite element simulations, and in vitro studies. Unfortunately, such types of research contribute minimally to the establishment of strong, evidence-based clinical guidelines.

Furthermore, findings from in-house aligner systems have varied considerably, especially in terms of the precision of orthodontic tooth movement (OTM) and the overall effectiveness of the appliances. Due to the inconsistencies and limited scope of current literature, there is a clear need to enhance the quality and reliability of available evidence in this area.[4]

For teeth to move in the way that is intended, clear aligners (CAs) must apply a constant, regulated force. Many thermoplastic materials, such as polyethylene terephthalate glycol (PETG), thermoplastic polyurethane (TPU), polypropylene, and polycarbonate, are used to make them. The introduction of novel materials with good mechanical qualities has improved CAs' clinical performance.[5] Nevertheless, creating serial models and cutting the aligners at each level along the gingival edge require a lot of time and work due to the traditional fabrication technique, which requires vacuum thermoforming thermoplastic materials.

Furthermore, it may be challenging to forecast the treatment outcomes of the CAs due to the unanticipated changes in their physical properties that may arise from the thermoforming process. Following the thermoforming process, thermoplastic materials exhibit varying degrees of shrinkage and expansion, which may have an impact on the aligner's thickness and fit.[6]

Clinically significant elements that contribute to improving the predictability of CA effectiveness are their thickness and gap width. The pressures and moments required for tooth movement can vary depending on the thickness of CA efficient force transfer to the teeth is made possible by the snug fit between tooth surfaces and CA, which also serves as an efficient anchor.[7] Since translucency and color stability are frequently prioritized by patients seeking orthodontic treatment, translucency is also regarded as a critical clinical component.

Various aligner sheets shows decrease in thickness in specific areas in extrusion direction depending on the amount of undercuts in the model as the strain introduced during manufacturing is released during thermoforming. This decrease in thickness of aligners depends on the sheet and model installation, direction specially in case of severely proclined incisors owing to biomechanical constraints. The predictability of retraction of incisors in such cases will greatly be affected by the thickness of aligners on the labial side of the incisors where the undercuts are present generally.[8]

Changes in aligner thickness—whether an increase or decrease—can significantly influence several clinical aspects, including the overall effectiveness of the aligner, the level of pain experienced by the patient, the magnitude of orthodontic tooth movement, and the retention or fit of the appliance. These variables are critical in determining treatment success and patient satisfaction.[9]

The primary objective of the present study is to investigate how variations in dental undercuts impact the required thickness of clear aligners. By examining the relationship between undercut anatomy and aligner thickness, the study aims to provide insights into how anatomical differences influence aligner fit, force distribution, and mechanical behavior during treatment. Understanding this interaction could help in customizing aligner design for improved clinical outcomes and patient comfort.

Aim

To investigate how the presence of undercuts affects the final thickness of clear aligners following the thermoforming process, using dental models with varying degrees of angulation.

Objectives

1. To assess the influence of undercuts on the thickness of thermoformed aligners across models with different angulations.
2. To analyze and compare the variations in aligner thickness specifically in the regions of tooth 11 and tooth 16 under varying angulation conditions.

Materials And Methodology

Materials

1. 20 Aligners -0.8 mm –(Erkodur-Al® – Erkodent Erich Kopp GmbH, Germany)
2. Four - 3D Printed Resin models of same patient
3. Dental stone
4. Thermoforming machine (BIOSTAR)
5. Digital Vernier calipers.

Mathedology

In this study, we utilized a 0.8 mm thick aligner sheet made of Erkodur-al material, which is the most commonly used aligner material in our region. Four identical resin models were fabricated from the same patient with proclined maxillary incisors and noticeable undercuts. These models were labeled as Model A, Model B, Model C, and Model D. It is well established that as the proclination of upper incisors increases, the degree of undercut also increases.

The standard inclination of the maxillary central incisors, measured from the base of the model, was found to be 120˚ and was designated as Model A. To create models with different angulations, the base of the remaining three models was incrementally increased using dental stone and then trimmed to achieve specific angulations of 110˚, 100˚, and 90˚ respectively:

1. Model A: Exhibited an angulation of 120˚ between the labial surface of the central incisor and the base of the model.
2. Model B: Had an angulation of 110˚, which is 10˚ less than Model A, resulting in a slight reduction in undercut.
3. Model C: Displayed an angle of 100˚, 20˚ less than Model A, with a more noticeable decrease in undercut compared to Model B.
4. Model D: Formed with an angle of 90˚, 30˚ less than Model A, presenting the least amount of undercut among the models.

Thermoforming of 0.8 mm Erkodur aligner sheets was performed directly on these models, with their modified dental stone bases left intact. A total of 20 aligners were produced, with five aligners fabricated for each model group. Upon completion of all laboratory procedures, the thickness of the thermoformed aligners was measured at two specific

Volume 8, Issue 5; September-October 2025; Page No 175-185

locations: the cervical region of tooth 11 and the cervical region of tooth 16. Measurements were recorded using a digital vernier caliper, and the resulting data were systematically documented for analysis.

Results

Table 1: comparison of aligner thickness at varying degrees in 11

Angulations	N	Mean	Std. Deviation	p-value
90	5	.6200	.04472	0.001*
100	5	.5200	.08367	
110	5	.4000	.07071	
120	5	.2400	.05477	

Kruskal wallis test; p-value ≤0.05 is statistically significant; *denotes significance

Graph 1: comparison of aligner thickness at varying degrees in 11

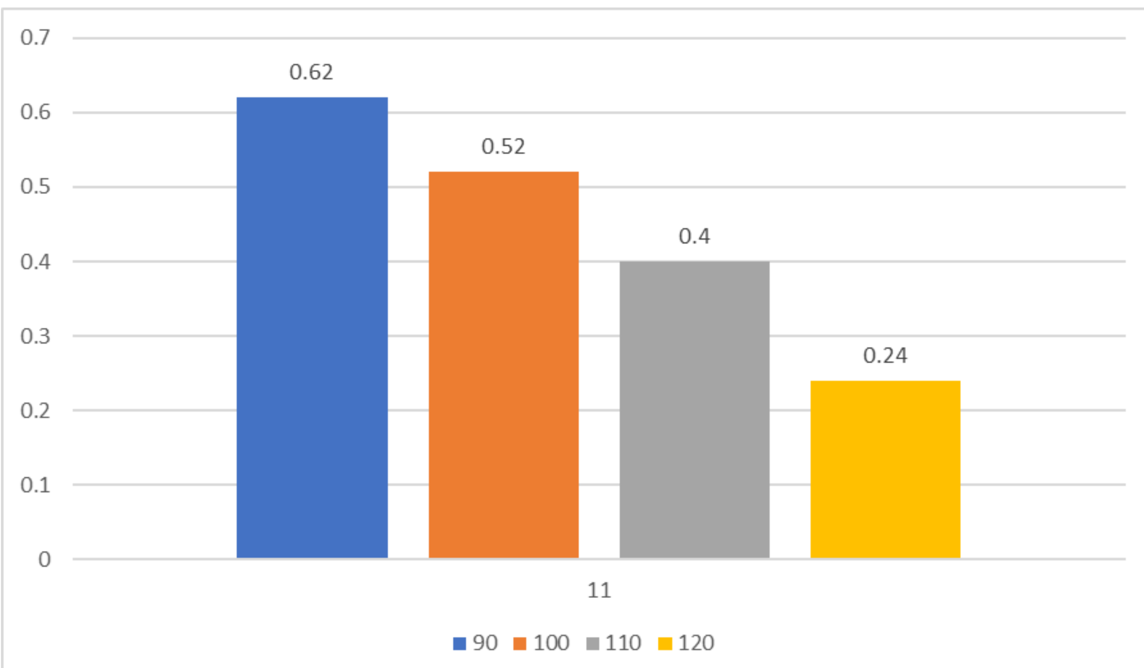

Table 1 and graph 1 depicts the comparison of aligner thickness at varying degrees in 11 using Kruskal wallis test. In 11, thickness of aligner is more at 90 degree (0.62) followed by 100 degree (0.52), 110 degree (0.4) and aligner thickness is least at 120 degree (0.24) and this difference is statistically significant (p=0.001).

Table 2: comparison of aligner thickness at different degrees in 16

Angulations	N	Mean	Std. Deviation	p-value

Volume 8, Issue 5; September-October 2025; Page No 175-185

90	5	.6000	.00000	0.222
100	5	.5460	.06387	
110	5	.5000	.10000	
120	5	.5400	.05477	

Kruskal wallis test; p-value ≤0.05 is statistically significant; *denotes significance

Graph 2: comparison of aligner thickness at different degrees in 16

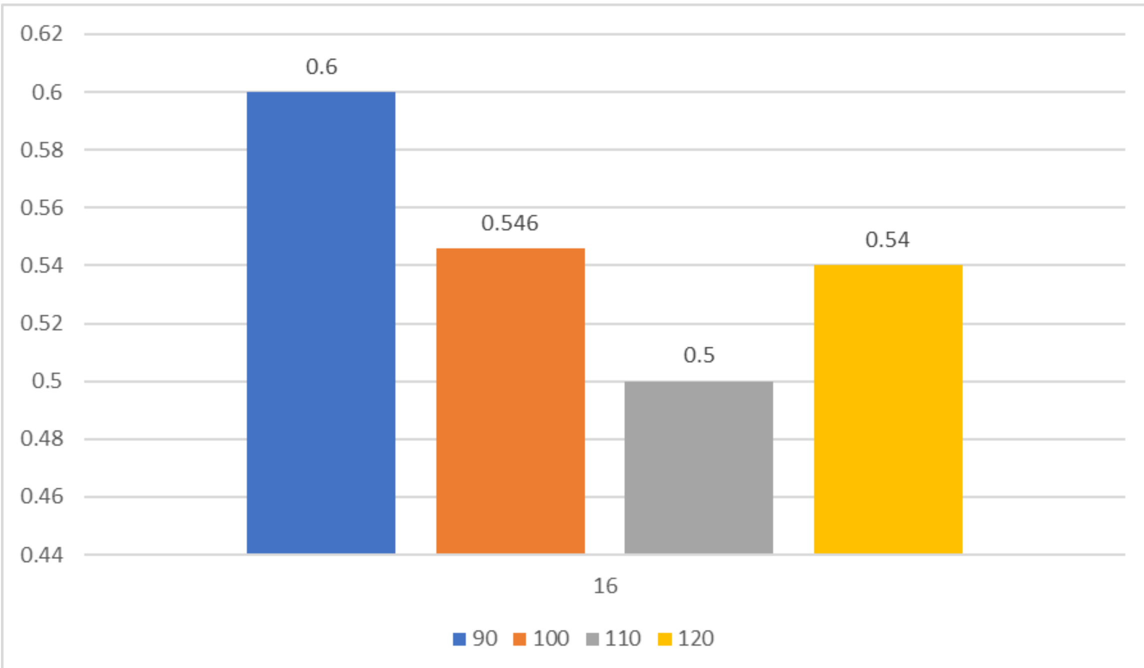

Table 2 and graph 2 depicts the comparison of aligner thickness at varying degrees in 16 using Kruskal wallis test. In 16, thickness of aligner is more at 90 degree (0.6) followed by 100 degree (0.546), 120 degree (0.54) and the least thickness of aligner is at 110 degree (0.5) and this difference is not statistically significant (p=0.222).

Table 3: comparison of aligner thickness at different degrees between 11 and 16

Angulations	Teeth	N	Mean	Std.deviation	p-value
90	11	5	.6200	.04472	0.317
	16	5	.6000	.00000	
100	11	5	.5200	.08367	0.572
	16	5	.5460	.06387	

110	11	5	.4000	.07071	0.116
	16	5	.5000	.10000	
120	11	5	.2400	.05477	0.007*
	16	5	.5400	.05477	

Mann whitney u test; p-value ≤0.05 is statistically significant; *denotes significance

Graph 3: comparison of aligner thickness at different degrees between 11 and 16

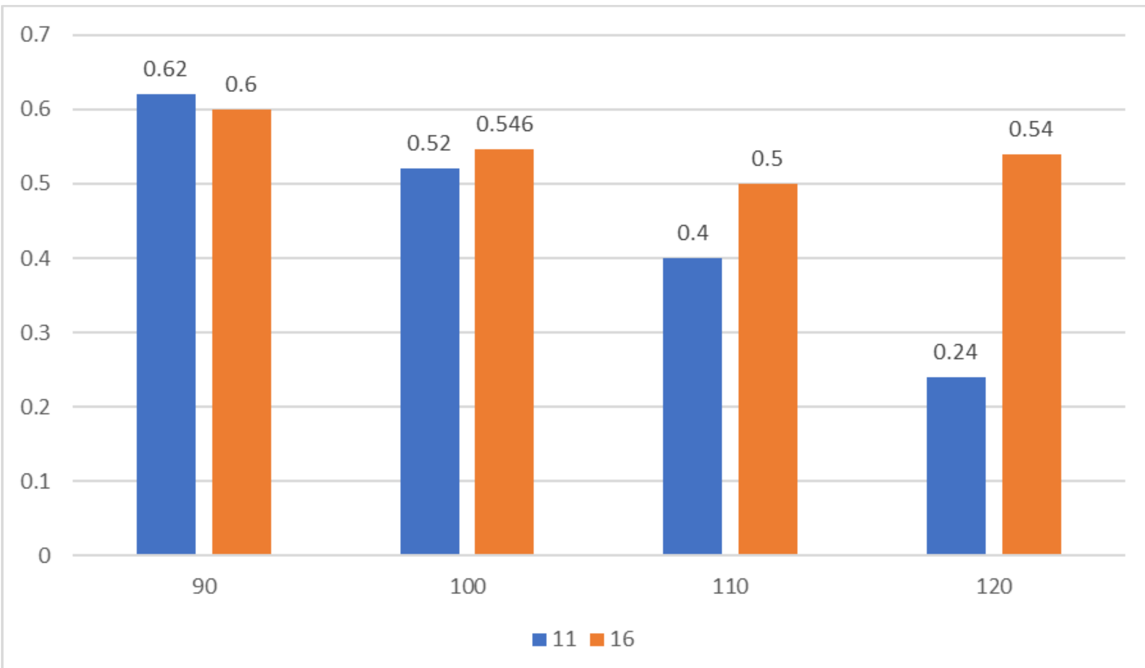

Table 3 and graph 3 describes the comparison of aligner thickness at different degree between 11 and 16 using mann whitney u test. At 90 degree, 11 (0.62) had more aligner thickness when compared to 16 (0.6) and is not statistically significant (p=0.317). At 100 degree,16 (0.546) had more aligner thickness when compared to 11 (0.52) and is not statistically significant (p=0.572). At 110 degree, 11 (0.4) had more aligner thickness when compared to 16 (0.5) and is not statistically significant (p=0.116). At 120 degree, 11 (0.24) had more aligner thickness when compared to 16 (0.54) and is statistically significant (p=0.007).

Table 4: comparison of aligner thickness at different degrees

Angulations	N	Mean	Std. Deviation	p-value
90	5	.6100	.02236	0.001*

100	5	.5320	.02950	
110	5	.4500	.03536	
120	5	.3900	.02236	

Graph 4: comparison of aligner thickness at different degrees

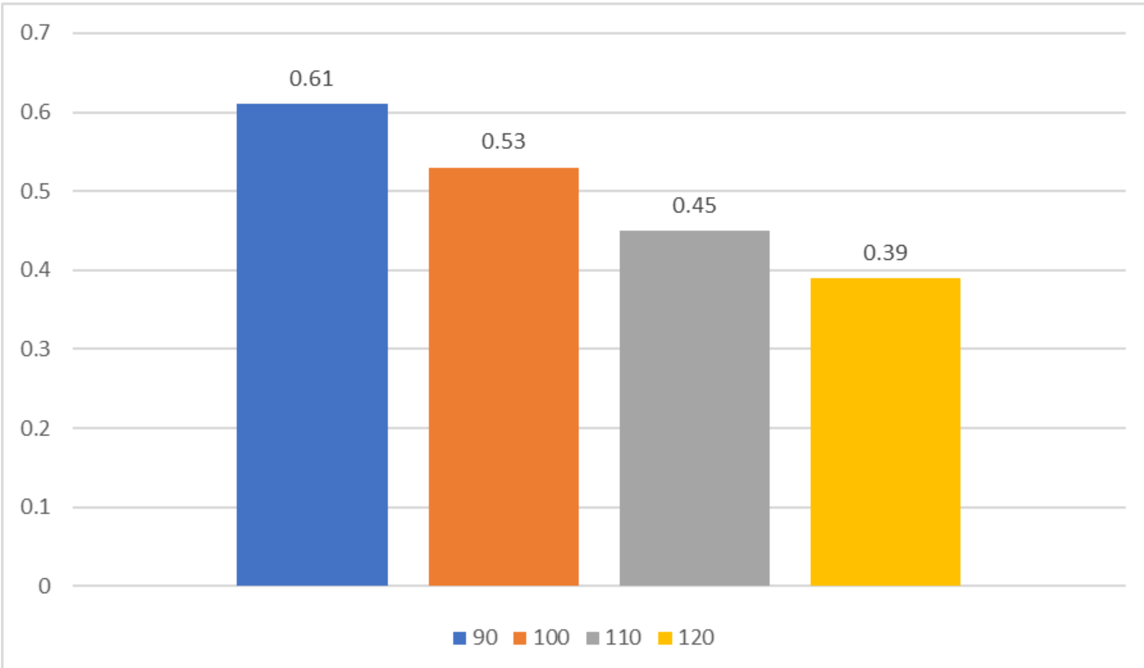

Table 4 and graph 4 describes the comparison of aligner thickness at different degrees using Kruskal wallis test. thickness of aligner is more at 90 degree (0.61) followed by 100 degree (0.53), 110 degree (0.45) and the least thickness of aligner is at 120 degree (0.39) and this difference is statistically significant (p=0.001).

Discussion

The effectiveness of clear aligner therapy (CAT) is influenced by a range of factors, including the morphology of the teeth, the type of tooth movement involved, the design and placement of attachments, the thickness of the aligners, and both clinician- and patient-related variables. Studies and manufacturer specifications indicate that aligner thickness typically varies between 0.5 mm and 1.5 mm. Additionally, the design features of the aligner, such as the height of its gingival margins (ranging from 0 to 4 mm above the gingival zenith) and whether the margins are scalloped or straight, can significantly affect the aligner's fit, the way orthodontic forces are applied, and the overall efficiency of tooth movement.

Contemporary orthodontics places a strong emphasis on delivering treatment that is not only effective but also comfortable and satisfactory for patients, thereby enhancing their quality of life. Nonetheless, any discomfort or pain during orthodontic treatment can adversely affect this quality of life. Among the factors that determine the success of CAT, patient compliance is considered to be the most essential. To better meet individual patient needs and improve treatment outcomes, tools such as patient questionnaires can be instrumental in assessing expectations and guiding personalized care.[10]

Variations in aligner thickness—either increasing or decreasing—can impact several key clinical outcomes. These include the effectiveness of tooth movement, the amount of discomfort or pain reported

Volume 8, Issue 5; September-October 2025; Page No 175-185

by the patient, the degree of movement achieved, and the aligner's retention or adaptation to the dental arch. Each of these elements plays a vital role in determining the overall success of the therapy and the patient's satisfaction.

This study specifically aims to explore how differences in dental undercuts affect the final thickness of clear aligners after the thermoforming process. By evaluating the correlation between the anatomical characteristics of undercuts and aligner thickness, the study seeks to provide a deeper understanding of how these variations influence aligner fit, the distribution of orthodontic forces, and the aligner's mechanical performance during treatment. Gaining insights into this relationship may allow for more precise and individualized aligner fabrication, ultimately enhancing both clinical effectiveness and patient comfort.

Table 1 and Graph 1 reveal a statistically significant difference in aligner thickness at tooth 11 (maxillary right central incisor) across models with varying degrees of labial surface inclination. The greatest aligner thickness was observed at 90° (0.62 mm), followed by 100° (0.52 mm), 110° (0.40 mm), and the least at 120° (0.24 mm). The Kruskal-Wallis test confirmed the significance of this pattern with a p-value of 0.001, indicating that undercut depth directly impacts aligner thickness during the thermoforming process.

This inverse relationship between incisal angulation and aligner thickness is consistent with previous findings. As the incisor becomes more proclined (higher angle), the depth of the undercut increases.[11] During thermoforming, the heated aligner sheet stretches more significantly over these deeper undercuts, particularly in the labial cervical region. This results in material thinning in areas of high curvature or pronounced anatomical contours. Lombardo et al. (2017)[12] demonstrated that aligner thickness decreases significantly in the extrusion or draw direction when the material is forced to conform over sharp anatomical changes such as proclined incisors.

The clinical relevance of this phenomenon is critical. Thinner aligners, particularly in the labial region of proclined incisors, may reduce the magnitude and consistency of force delivery to the tooth. According to Elshazly TM et al (2024)[13], decreased aligner thickness compromises the transmission of controlled forces, potentially leading to inefficient or unpredictable tooth movement, especially during retraction or torque control.

Moreover, the reduced material thickness in highly proclined cases (e.g., 120°) may also affect retention, since a thinner aligner provides less elastic rebound and grip over the tooth morphology. Ryu JH et al. (2018)[14] noted that force delivery is not only dependent on the aligner material but also on its thickness at specific regions, emphasizing the need for precise thermoforming techniques or potential material reinforcement in undercut zones.

Table 2 and Graph 2 present the comparison of aligner thickness at different incisal angulations (90°, 100°, 110°, 120°) specifically at the cervical region of tooth 16. The highest mean thickness was recorded at 90° (0.6 mm), followed by 100° (0.546 mm), 120° (0.540 mm), and the lowest at 110° (0.5 mm). However, these differences were not statistically significant ($p = 0.222$), indicating that, unlike anterior regions such as tooth 11, the undercuts created by angulation changes had a less pronounced effect on thickness in posterior teeth.

The absence of significant variation in thickness in tooth 16 can be attributed to its relatively less complex morphology and reduced undercut depth when compared to the proclined central incisor (tooth 11).[15] Posterior teeth generally lack the steep labial inclinations and prominent undercuts that affect thermoformed material flow during manufacturing, especially in the extrusion direction, as supported by Lombardo et al. (2017), who emphasized that aligner thickness is more likely to decrease in areas with complex undercuts during thermoforming due to stretching and thinning of the material.

Furthermore, since posterior segments of the arch typically undergo less aggressive movement and have shorter vertical height, there is less deformation of the aligner sheet in these regions. This aligns with findings by Bucci et al. (2019)[6], who demonstrated that aligner thickness variation is influenced by both anatomical curvature and pressure distribution during thermoforming, with more substantial thickness changes seen in anterior curved surfaces.

From a clinical standpoint, while thickness variation in posterior teeth may not be statistically significant, it

Volume 8, Issue 5; September-October 2025; Page No 175-185

still holds biomechanical importance. Even slight differences can affect occlusal settling, anchorage, and retention, particularly in sequential distalization cases or when molar tipping control is required.

Table 3 and Graph 3 compare the aligner thickness at two distinct tooth positions—tooth 11 (central incisor) and tooth 16 (first molar)—under varying angulation conditions (90°, 100°, 110°, and 120°). Among the four angulations, a statistically significant difference was found only at 120°, where the aligner thickness at tooth 11 (0.24 mm) was significantly thinner than at tooth 16 (0.54 mm) ($p = 0.007$). At other angulations, differences were not statistically significant.

This observation highlights how the severity of anatomical undercuts directly impacts aligner adaptation during thermoforming. At 120°, the incisor exhibits maximum proclination, resulting in a deeper labial undercut that leads to substantial thinning of the aligner material as it stretches over this contour. In contrast, the molar, being a bulkier and more vertically oriented tooth, presents fewer undercuts and minimal curvature, allowing the aligner to maintain its original thickness more effectively.

Studies such as Bandić R et al. (2024)[16] have demonstrated that aligner adaptation is sensitive to model geometry, particularly in areas with pronounced convexities. These regions are more prone to thinning due to material strain during thermoforming. James Grant et al. (2023) [17] also noted that steep undercuts on labial surfaces tend to create uneven aligner thicknesses, which could reduce the mechanical efficiency of force delivery.

This anterior-posterior disparity in thickness is not only a laboratory observation—it has clinical consequences. In thinner areas (as seen in the labial surface of tooth 11 at 120°), the aligner's mechanical stiffness decreases, potentially reducing the force applied for incisor retraction, tipping control, or torque application. As Li J et al. (2024) reported, force expression in aligner therapy is highly dependent on regional stiffness, which is in turn governed by material thickness and how well the appliance adapts to the tooth surface.

Interestingly, tooth 16 showed relatively stable thickness values across all angulations, suggesting that posterior tooth morphology may buffer against thermoforming-induced thickness variation. The molar's broader surface area and less dramatic contour changes help preserve aligner geometry, maintaining consistent force output and retentive qualities.

From a clinical planning perspective, this finding emphasizes the importance of incorporating undercut management in treatment protocols—especially in anterior regions. Strategies might include:

- Pre-treatment reduction of excessive proclination where feasible
- Use of pressure compensation zones or localized reinforcement in high-undercut areas

Table 4 and Graph 4 present a collective analysis of aligner thickness across four angulations—90°, 100°, 110°, and 120°—regardless of tooth location. The data show a statistically significant trend ($p = 0.001$) in which aligner thickness progressively decreases with increasing angulation:

This downward trend illustrates a clear inverse correlation between incisal angulation and aligner thickness, confirming that greater undercut depth, commonly associated with increased proclination of teeth, leads to more material stretching and thinning during thermoforming.

These findings are aligned with Singh Deepshikha KrishnaKailash (2024)[19], who emphasized that aligners are subject to non-uniform stress distribution during vacuum forming, particularly over steep or undercut contours. This distortion results in thinner regions in areas where the thermoplastic material is stretched more significantly. Likewise, Wang et al[20] (2025) observed that the thickness of aligners fabricated on models with exaggerated incisal inclinations showed significant reduction, especially on the labial surfaces of anterior teeth.

This trend is not only a fabrication phenomenon—it has critical clinical implications. Thinner aligners in regions of severe proclination:

Moreover, Elshazly TM et al. (2024)[13] suggested that force predictability in aligner therapy is significantly affected by material thickness. Their study noted that even 0.1 mm differences in thickness can influence tooth movement magnitude and accuracy.

Conclusion

This study explored the influence of undercut anatomy—created by varying incisal angulations—on

Volume 8, Issue 5; September-October 2025; Page No 175-185

the final thickness of clear aligners after the thermoforming process. The findings clearly demonstrate that as the proclination of anterior teeth increases, resulting in deeper undercuts, the thermoformed aligner material undergoes significant thinning, particularly in the labial cervical region of tooth 11. In contrast, posterior teeth such as tooth 16 exhibited relatively stable thickness values across different angulations, likely due to less anatomical curvature and fewer undercuts.

The most substantial thickness reduction occurred at 120° angulation, where the aligner sheet was stretched the most during forming. Statistically significant differences in thickness between anterior and posterior teeth at this angulation underscore the biomechanical implications of undercut-induced material distortion. Thinner regions in anterior teeth may compromise force delivery, control, and appliance retention—ultimately affecting the predictability and efficiency of orthodontic treatment with aligners.

These results highlight the need for clinicians to consider tooth morphology and undercut severity when planning clear aligner therapy. Incorporating design adaptations—such as using thicker or reinforced materials in high-undercut zones, adjusting thermoforming parameters, or digitally compensating for expected thinning—may enhance aligner performance and clinical outcomes.

Future research using advanced imaging techniques like micro-CT or finite element modeling could further quantify thickness changes in complex anatomical regions and help establish standardized guidelines for aligner fabrication in cases with significant proclination or undercut challenges

REFERENCES

1. Kesling HD. The philosophy of the tooth positioner appliance. Am J Orthod Oral Surg. 1945;31(6):297–304.
2. Shukla A, Maysan S, Kumari U, Bokieva A, Kalaria N, Patel M. Application of CAD CAM in dentistry. *South Eastern European Journal of Public Health* (SEEJPH). 2025;26(S1):6591. Posted 2025 Jan 5. ISSN: 2197-5248.
3. Nakornnoi T, Srirodjanakul W, Chintavalakorn R, Santiwong P, Sipiyaruk K. The biomechanical effects of clear aligner trimline designs and extensions on orthodontic tooth movement: a systematic review. BMC Oral Health. 2024 Dec 20;24(1):1523. doi: 10.1186/s12903-024-05274-7. PMID: 39707339; PMCID: PMC11662417.
4. Basu P, Roychoudhury S, Amit K, Krishnakailash SD, Goel A. Accuracy evaluation of orthodontic movements with in-house aligners system: A prospective observational study. *J Adv Med Dent Scie Res*. 2025; doi:10.21276/jamdsr.
5. Delgado JI, Kehyaian P, Fernández-Blázquez JP. Thermoplastics for Clear Aligners: A Review. Polymers (Basel). 2025 Jun 17;17(12):1681. doi: 10.3390/polym17121681. PMID: 40574208; PMCID: PMC12196624.
6. Bucci, R., Rongo, R., Levatè, C. *et al.* Thickness of orthodontic clear aligners after thermoforming and after 10 days of intraoral exposure: a prospective clinical study. *Prog Orthod.* **20**, 36 (2019). https://doi.org/10.1186/s40510-019-0289-6.
7. Park SY, Choi SH, Yu HS, Kim SJ, Kim H, Kim KB, Cha JY. Comparison of translucency, thickness, and gap width of thermoformed and 3D-printed clear aligners using micro-CT and spectrophotometer. Sci Rep. 2023 Jul 5;13(1):10921. doi: 10.1038/s41598-023-36851-5. PMID: 37407694; PMCID: PMC10322848.
8. Yan, X., Zhang, X., Ren, L. *et al.* Effectiveness of clear aligners in achieving proclination and intrusion of incisors among Class II division 2 patients: a multivariate analysis. *Prog Orthod.* **24**, 12 (2023). https://doi.org/10.1186/s40510-023-00463-6
9. Cengiz SM, Goymen M. The effectiveness of orthodontic treatment with clear aligners in different thicknesses. Sci Rep. 2025 Feb 1;15(1):3958. doi: 10.1038/s41598-025-86345-9. PMID: 39893227; PMCID: PMC11787305.

Volume 8, Issue 5; September-October 2025; Page No 175-185

10. Olawade DB, Leena N, Egbon E, Rai J, Mohammed APEK, Oladapo BI, Boussios S. AI-Driven Advancements in Orthodontics for Precision and Patient Outcomes. Dent J (Basel). 2025 Apr 30;13(5):198. doi: 10.3390/dj13050198. PMID: 40422618; PMCID: PMC12110745.
11. Hussels W, Nanda RS. Effect of maxillary incisor angulation and inclination on arch length. *Am J Orthod Dentofacial Orthop*. 1987;91(3):233–9. doi:10.1016/0889-5406(87)90451-3.
12. Lombardo L, Arreghini A, Ramina F, Huanca Ghislanzoni LT, Siciliani G. Predictability of orthodontic movement with orthodontic aligners: a retrospective study. Prog Orthod. 2017 Nov 13;18(1):35. doi: 10.1186/s40510-017-0190-0. PMID: 29130127; PMCID: PMC5682257.
13. Elshazly TM, Bourauel C, Ismail A, Ghoraba O, Aldesoki M, Salvatori D, Elattar H, Alhotan A, Alkabani Y. Effect of material composition and thickness of orthodontic aligners on the transmission and distribution of forces: an in vitro study. Clin Oral Investig. 2024 Apr 19;28(5):258. doi: 10.1007/s00784-024-05662-x. PMID: 38637429; PMCID: PMC11026231.
14. Ryu JH, Kwon JS, Jiang HB, Cha JY, Kim KM. Effects of thermoforming on the physical and mechanical properties of thermoplastic materials for transparent orthodontic aligners. Korean J Orthod. 2018 Sep;48(5):316-325. doi: 10.4041/kjod.2018.48.5.316. Epub 2018 Aug 8. PMID: 30206530; PMCID: PMC6123073.
15. ALShami A, ALHarthi S, Binshabaib M, Wahi M. London: IntechOpen; 2019. doi:10.5772/intechopen.87153.
16. Bandić R, Vodanović K, Vuković Kekez I, Medvedec Mikić I, Galić I, Kalibović Govorko D. Thickness Variations of Thermoformed and 3D-Printed Clear Aligners. Acta Stomatol Croat. 2024 Jun;58(2):145-155. doi: 10.15644/asc58/2/4. PMID: 39036327; PMCID: PMC11256873.
17. Grant, J., Foley, P., Bankhead, B. *et al.* Forces and moments generated by 3D direct printed clear aligners of varying labial and lingual thicknesses during lingual movement of maxillary central incisor: an in vitro study. *Prog Orthod.* **24**, 23 (2023). https://doi.org/10.1186/s40510-023-00475-2
18. Li J, Si J, Xue C, Xu H. Seeking orderness out of the orderless movements: an up-to-date review of the biomechanics in clear aligners. Prog Orthod. 2024 Nov 18;25(1):44. doi: 10.1186/s40510-024-00543-1. PMID: 39551881; PMCID: PMC11570571.
19. Singh D, KrishnaKailash, Roychoudhury S, Amit K, Basu P, Santosh GK, Yousuf K**.** Assessment of change in thickness of aligner using vacuum and pressure thermoforming techniques: An in-vitro study. *J Adv Med Dent Scie Res.* 2025; doi:10.21276/jamdsr.
20. Wang Y, Long H, Zhao Z, Bai D, Han X, Wang J, Fang B, Jin Z, He H, Bai Y, Li W, Hu M, Zhou Y, Ai H, Liu Y, Cao Y, Lin J, Li H, Guo J, Lai W. Expert consensus on the clinical strategies for orthodontic treatment with clear aligners. Int J Oral Sci. 2025 Mar 13;17(1):19. doi: 10.1038/s41368-025-00350-2. PMID: 40074738; PMCID: PMC11904224.