

Biomechanical Comparison of Composite Attachment Designs for Bodily Distalization of the Maxillary Canine Using Clear Aligners: A Three-Dimensional Finite Element Study

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Abstract

Background: Clear aligner therapy has emerged as a popular orthodontic treatment modality because of its esthetics, comfort, and improved oral hygiene maintenance. Despite these advantages, achieving predictable bodily movement of teeth remains challenging. Distalization of the maxillary canine is a critical stage in extraction-based orthodontic treatment and often requires enhanced biomechanical control. Composite attachments are commonly incorporated into aligner therapy to improve force transmission and movement predictability.

Aim: To evaluate and compare the effectiveness of different composite attachment designs in achieving bodily distalization of the maxillary canine during clear aligner therapy using finite element analysis.

Materials and Methods: A three-dimensional finite element model of the maxillary arch was constructed using cone-beam computed tomography data obtained from a patient requiring maxillary first premolar extraction and canine distalization. Four models were generated: Model 1 (semicircular couple attachment), Model 2 (vertical rectangular attachment), Model 3 (horizontal rectangular attachment), and Model 4 (Clear aligner without attachment). Distal displacement, movement pattern, and anchorage preservation were evaluated under standardized loading conditions.

Results: Attachment morphology significantly influenced the quality of canine distalization. The vertical rectangular attachment demonstrated the most favorable biomechanical behavior and produced controlled bodily movement of the canine. Horizontal rectangular and semi-circular attachments exhibited controlled tipping, whereas the no-attachment model demonstrated uncontrolled tipping and greater anchorage loading. The vertical rectangular attachment also exhibited superior anchorage preservation compared with the other configurations.

Conclusion: Among the attachment configurations evaluated, the vertical rectangular attachment demonstrated superior effectiveness in achieving bodily distalization of the maxillary canine and may be considered the most favorable attachment design for extraction-based aligner therapy.

Keywords: Clear aligners, Composite attachments, Canine distalization, Bodily movement, Finite element analysis

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INTRODUCTION

The increasing demand for esthetic orthodontic treatment has led to the widespread use of clear aligner therapy as an alternative to conventional fixed appliances. Clear aligners offer several advantages, including improved esthetics, enhanced patient comfort, reduced soft tissue irritation, and easier maintenance of oral hygiene. However, despite their popularity, certain orthodontic tooth movements remain difficult to achieve predictably with aligners.

Canine distalization is an important component of orthodontic treatment, particularly in extraction cases requiring space closure. Successful distalization requires bodily movement of the canine, in which the crown and root move simultaneously in the desired direction. Inadequate

biomechanical control often results in uncontrolled tipping, prolonged treatment duration, increased need for refinements, and compromised treatment outcomes.

Unlike fixed orthodontic appliances that utilize brackets and archwires to generate force systems, clear aligners rely on programmed deformation of thermoplastic material. Consequently, force expression and root control may be limited. To overcome these limitations, composite attachments are routinely incorporated into aligner therapy. Attachments modify tooth morphology and enhance mechanical interaction between the aligner and tooth surface, thereby improving retention and force delivery.

Various attachment designs have been proposed; however, the influence of attachment morphology on canine distalization remains incompletely understood. Understanding the biomechanical behavior of different attachment designs is essential for optimizing treatment efficiency and improving clinical outcomes.

Finite element analysis (FEA) is a valuable tool for investigating orthodontic biomechanics. It enables simulation of tooth movement under controlled conditions and allows detailed evaluation of movement patterns that cannot be directly measured clinically.

Therefore, the present study was undertaken to evaluate and compare different composite attachment designs for achieving bodily distalization of the maxillary canine using finite element analysis.

MATERIALS AND METHODS

Study Design

The present investigation was designed as a three-dimensional finite element study to evaluate the influence of different attachment designs on canine distalization during clear aligner therapy.

Inclusion Criteria

- Angle's Class II Division 1 malocclusion
- Permanent dentition
- Requirement of maxillary first premolar extraction
- Skeletal Class I relationship
- Normal temporomandibular joint morphology

Model Construction

Cone-beam computed tomography data from a patient meeting the inclusion criteria were obtained and converted into a three-dimensional stereolithographic model. Anatomically accurate representations of the maxillary dentition, periodontal ligament, cortical bone, cancellous bone, and supporting structures were reconstructed.

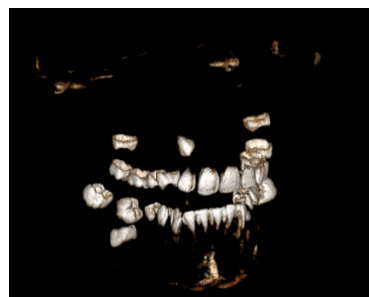
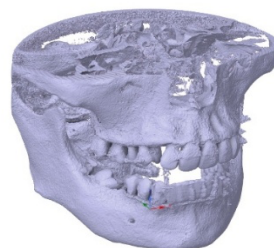


Figure no 1: 3D geometric surface model of the maxilla obtained through CBCT

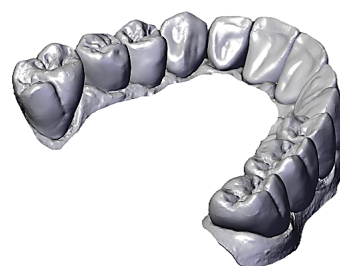


Figure no 2: The geometric model impregnated with materialistic properties

A digital clear aligner was designed and assembled with the maxillary dentition. Four finite element models were generated:

Model 1: Semi-circular attachment

Model 2: Vertical rectangular attachment

Model 3: Horizontal rectangular attachment

Model 4: Clear aligner without attachment

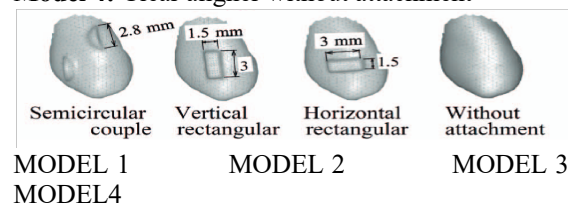


Figure No 3: Finite Element Models Representing Various Attachment Configurations

The attachment designs were standardized and positioned on the maxillary canine.

Finite Element Analysis

Meshing of all models was performed using ANSYS software. Standardized material properties were assigned to enamel, dentin, periodontal ligament, alveolar bone, aligner material, and composite attachments.

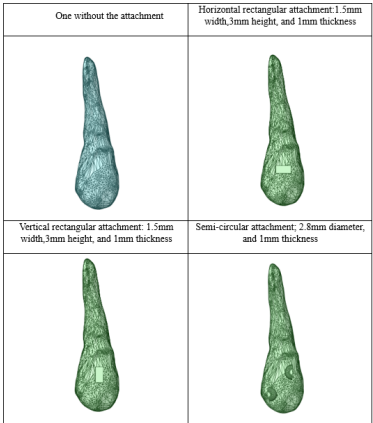


Figure No 4: Geometric Representation of Composite Attachments Used in the Finite Element Analysis

A distalization force was applied under identical loading conditions to all models. The biomechanical response of the canine and adjacent teeth was analyzed.

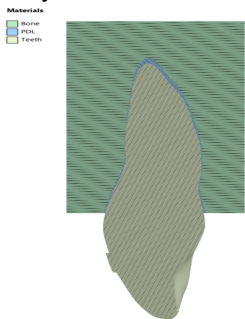


Figure no 5: Finite Element Representation of Tooth-PDL-Bone Complex Under Applied Load

Outcome Measures

The following parameters were evaluated:

- Distal displacement of the maxillary canine
- Pattern of canine movement
- Quality of bodily movement
- Anchorage preservation

RESULTS

Distalization of the Maxillary Canine

The attachment design significantly influenced the pattern of canine movement achieved during distalization.

Table 1. Distal displacement and movement pattern of the maxillary canine

Model	Distal Displacement (mm)	Movement Pattern
No Attachment	0.142	Uncontrolled tipping

Model	Distal Displacement (mm)	Movement Pattern
Horizontal Rectangular	0.125	Controlled tipping
Vertical Rectangular	0.114	Bodily movement
Semi-Circular	0.129	Controlled tipping

The no-attachment model demonstrated the greatest amount of distal crown displacement. However, the movement pattern was characterized by uncontrolled tipping, indicating inadequate root control.

The horizontal rectangular attachment demonstrated improved movement control compared with the control model. Nevertheless, controlled tipping remained evident.

The vertical rectangular attachment demonstrated the most favorable biomechanical performance. Distalization occurred with improved root control, resulting in bodily movement of the canine. This attachment exhibited the most efficient movement pattern among all configurations evaluated.

The semi-circular attachment demonstrated moderate effectiveness. Although movement control improved relative to the control model, bodily movement was not achieved.

Anchorage Preservation

The control model exhibited greater displacement of adjacent teeth, indicating increased anchorage loss. All attachment configurations improved anchorage preservation compared with the no-attachment model. Among the evaluated designs, the vertical rectangular attachment demonstrated the most favorable anchorage behavior during canine distalization. These findings suggest that improved aligner engagement contributes to more efficient force distribution and reduced unwanted tooth movement.

DISCUSSION

Clear aligner therapy has become one of the most significant advancements in modern orthodontics. Despite increasing popularity, achieving predictable bodily movement remains a challenge because force expression differs substantially from conventional fixed appliance therapy.

Canine distalization is particularly demanding because successful movement requires simultaneous control of both the crown and root. When orthodontic forces are applied without adequate moment control, tipping movements occur rather than true translation. Therefore, biomechanical auxiliaries such as composite attachments play an important role in aligner therapy.

The present study demonstrated that attachment design significantly influences the quality of canine distalization. The no-attachment model exhibited uncontrolled tipping despite demonstrating the

greatest distal crown displacement. This finding indicates that greater displacement alone does not necessarily represent efficient orthodontic movement. Lack of sufficient aligner engagement likely resulted in force application predominantly at the crown level, leading to tipping rather than bodily movement.

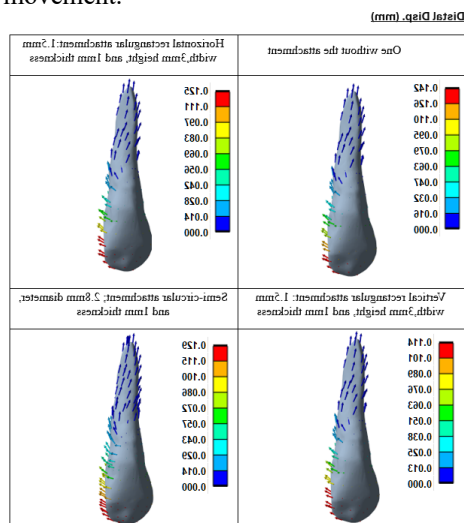


Figure No 6: Comparative Evaluation of Tooth Movement and Periodontal Ligament Stress Across Attachment Models-Total displacement

The horizontal rectangular attachment improved force transmission between the aligner and tooth surface. Increased contact area enhanced retention and reduced aligner slippage. However, complete bodily movement was not achieved, indicating that the generated force system was insufficient to provide optimal root control.

Among all attachment configurations evaluated, the vertical rectangular attachment demonstrated the most favorable biomechanical behavior. Improved aligner engagement facilitated enhanced control of the force system, resulting in bodily movement of the canine. The attachment geometry allowed more effective generation of counteracting moments required to control root position during distalization. This finding suggests that vertical rectangular attachments provide superior biomechanical efficiency when bodily canine movement is desired. The semi-circular attachment demonstrated intermediate performance. Although it improved movement control compared with the no-attachment model, its rounded morphology reduced mechanical engagement and limited its effectiveness in producing bodily movement.

Another important finding was the influence of attachment design on anchorage preservation. The vertical rectangular attachment demonstrated reduced displacement of adjacent teeth compared with the other models, suggesting more favorable distribution of orthodontic forces. Effective anchorage control is essential during canine distalization because uncontrolled reactive forces

may compromise treatment efficiency and prolong treatment duration.

The findings of the present study are consistent with previous investigations that have reported improved translational control with rectangular attachment designs. Collectively, these findings reinforce the importance of attachment selection in improving treatment predictability during aligner therapy.

Clinical Significance

The findings of this study have direct clinical relevance for orthodontists utilizing clear aligner therapy in extraction cases. Selection of an appropriate attachment design significantly influences treatment predictability and movement efficiency. Based on the present results, vertical rectangular attachments may be preferred when bodily distalization of the maxillary canine is the primary treatment objective.

Limitations

The present study was conducted using finite element analysis, which represents a simulated biomechanical environment. Biological responses such as periodontal ligament remodeling, bone adaptation, patient compliance, and variations in aligner wear schedules could not be completely reproduced. Therefore, the findings should be interpreted with caution and validated through future clinical studies.

Future Scope

Future investigations should include clinical trials evaluating the effectiveness of different attachment designs during canine distalization. Further research may also assess the influence of attachment size, position, and aligner material properties on the predictability of bodily tooth movement.

CONCLUSION

Within the limitations of this finite element study, it can be concluded that composite attachment design plays a significant role in determining the pattern and quality of maxillary canine distalization during clear aligner therapy.

The absence of attachments resulted in greater distal crown displacement; however, the movement was characterized by uncontrolled tipping, making it clinically less desirable. Although horizontal rectangular and semi-circular attachments improved movement control, they did not achieve true bodily movement of the canine.

Among the attachment configurations evaluated, the **vertical rectangular attachment** demonstrated the most favorable biomechanical performance by providing improved root control, effective bodily distalization, and better anchorage preservation.

Therefore, the use of a **vertical rectangular attachment** may be considered the most appropriate design when predictable bodily movement of the maxillary canine is the primary treatment objective during clear aligner therapy.

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