Original Article

The Effects of Different Attachment Geometries on Second Molar Uprighting in Clear Aligner Treatment: An In Vitro Study

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Abstract

Objective: Investigate the biomechanical impacts of various attachment designs on second molar uprighting, identify optimal geometry, and provide clinical guidelines for clear aligner treatment following first molar loss.

Methods: This in vitro study was conducted by using 3D-printed dental models with mesially tilted second molars. Five groups were designed based on attachment geometry: one without attachment, horizontal, inclined attachment, twin alternative, and two vertical. Clear aligners were fabricated and applied to each model to deliver uprighting forces. Pre- and post-treatment tooth positions were measured to a fixed reference point by using CBCT, and changes in mesiodistal inclination, buccolingual inclination, vertical, and mesiodistal distances were recorded. Statistical analysis was performed using the Kruskal-Wallis test followed by pairwise comparisons to identify significant differences among groups.

Results: The inclined attachment produced the greatest uprighting effect in mesiodistal inclination, indicating superior molar control compared to other geometries. Minimal buccolingual inclination change was observed in the single horizontal and inclined groups, while twin-type attachments showed greater deviation. Vertical positioning was largely maintained across groups, with no statistically significant differences. Mesiodistal distance varied between attachment types, with inclined and horizontal designs showing the greatest reduction. Overall, attachment geometry demonstrated measurable effects on molar movement across multiple dimensions.

Conclusions: The inclined attachment showed better performance in second molar uprighting compared with single horizontal, twin, and two vertical attachments. Attachment geometry significantly influences molar control.

Keywords: *Clear Aligner; Attachment Geometry; Orthodontic Tooth Movement and Biomechanics.*

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Introduction

Clear Aligner Treatment (CAT) is a method for straightening the teeth by using transparent, custom-made plastic aligners. The aligners move the teeth into the intended position by gradually exerting gentle force[1]. Among the benefits of CAT are virtually invisible braces that are comfortable to wear and detachable for brushing and eating, and this results in more hygienic treatment as compared to fixed orthodontics. This allows CAT to be utilized in treating a vast array of orthodontic issues[2].

The first permanent molars are highly prone to dental caries, which often results in their premature loss. The early loss of first molars in isolation is a prevalent issue globally, affecting from 8% to 21% of the population, with this variation reflecting differences in the age groups, populations studied, and other methodological variables[3]. This occurrence is likely due to these teeth being the first to emerge in the posterior of the mouth and can be attributed to enamel developmental issues such as molar incisor hypomineralization. The prevalence of this condition ranges from 2.4% to 40.2%[4,5]. As a result of this extraction, the second molar will tip to the extraction space. This condition is frequently observed in adults who are seeking orthodontic treatment and is linked to occlusal interference, periodontal issues, and difficulties in rehabilitating the edentulous area[6]. This tilting happens because of the loss of mesial support of the tooth, and it drifts forward under occlusal and eruptive forces, as the crown moves mesially and the root remains in distal. The degree of tipping may differ between patients depending on factors such as the timing of molar loss relative to second-molar eruption, the amount of available space, and the magnitude of functional and occlusal forces[7]. Furthermore, with the introduction of high-tech appliances, anchorage devices, and improved patient awareness of the risks associated with maxillofacial surgery, treating complex situations with orthodontic treatment has become more difficult in recent years[8].

Some drawbacks to conventional fixed orthodontic treatment for molar uprighting include the tilted molar's extrusion, unintended reciprocal movement of the anchorage units, the requirement for large appliances, and lengthier treatment times[9]. Another drawback of fixed orthodontic treatment is the development of white spot lesions around orthodontic attachments. In contrast, removable appliances such as clear thermoplastic aligners are easily removed, allowing patients to practice oral hygiene comfortably. Since patients do not experience any obstructions from brackets, bands, or arch wires, they may prevent their oral hygiene from deteriorating[10].

Some aligner systems use resin-bonded attachments. Attachments have been used to make sure that the appliance remains steady in its place on the teeth and to enhance CA's capability to perform certain movements that would otherwise be impossible. Unpredictable movements consist of rotation of round-shaped teeth (from an occlusal perspective), extrusion of teeth, and retention of aligners in those cases where teeth are short or do not have enough undercut. Only minimal tooth movement can be obtained when bonded attachments are absent from an aligner system[11].

Clear aligners are indicated to correct inclinations of the teeth to their normal position, movement that is considered difficult unless the correct attachment is used. Recent studies have focused on anterior teeth, and suitable attachment for correcting tilted second molars is controversial[12]. A limited number of researchers have explored the possibility of molar uprighting with clear aligners. For example, a recent case report described uprighting and protraction of a mandibular second molar using a dual approach that integrated aligners with an auxiliary cantilever arm, resulting in successful crown and root movement with high accuracy[13].

Systematic reviews highlight that attachments improve the effectiveness of aligners for specific movements, like mesiodistal tipping, root torque, and intrusion but their specific role in posterior uprighting has not been conclusively validated, showing the need for further investigation[11]. The objective of this study is to find the most suitable and efficient attachment geometries to correct this malocclusion with clear aligners.

Materials and methods

Preparing the typodont for this study began with the digital scanning of a standard typodont using the Shining 3D® Aoralscan 3™ intraoral scanner. This scanner, operated through the DentalOrder software, produced a high-quality OBJ file representing the initial morphology of the standard typodont model. (Figure 1:A). The scan was subsequently transferred into the MEDIT™ software version 3.0 (Medit Corp., Seoul, South Korea) to generate a digital working cast. In this digital working cast, the lower left molar region was eliminated. (Figure 1:B)

The digital working cast was then imported into Blender™ software version 3.6 LTS (Blender Foundation, Amsterdam, Netherlands), a 3D modeling software, to further prepare it for experimental use. In Blender, a supporting box structure was placed in the area of the missing molars, with dimensions sufficient to stabilize the addition of future components; the dimensions were w:14 mm, L:30 mm and H:19 mm[12].

Nine small wells of 2 mm × 2 mm × 2 mm were designed within the large box wall, four of them in the sagittal plane and four in the coronal plane, and one at the intersection of the two planes. (Figure 1:C). The aim of these cubes was to serve as radiographic reference markers during the study. This arrangement is necessary for comparing data from before and after the experiment in a scientific way. Following finalization of the digital design, the model was printed using a high-precision Microlay 3D printer with layer thicknesses of 100 microns using KeyModel Ultra™ dental model resin (Keystone Industries, USA). (Figure 1:D)

The first physical printed model was then used to make the typodonts. The spaces of the nine small cubes were filled with flowable composite— Esflow® (Spident Co., Ltd., Incheon, South Korea). Composite placement was done carefully to avoid gaps, and polymerization was performed using a Wiscure-1S+™ (Wismed, China) light-curing unit, ensuring the reference points remained fixed and visible under CBCT imaging. (Figure 2:A). Then typodont wax was used to fill the supporting box, serving as a base for seating a mandibular second molar tooth. After that, aluminum-based tooth was used in the study because this material has the ability to minimize scattering artifacts during CBCT imaging[15]. The tooth was manually positioned within the wax at an angle of 30 degrees to the horizontal reference plane, representing a typical malposition often encountered in clinical orthodontics in cases with early extraction of the permanent lower first molar[16]. (Figure 2:B)

Taking initial records

A Cone Beam Computed Tomography (CBCT) scan was taken to serve as the initial reference for evaluating the spatial relationship between the tilted mandibular second molar and the composite-filled reference cubes. The imaging was taken by using the VATECH® Pax-i3D™ CBCT (VATECH Co., Ltd., Korea) unit, operated through its default software, Ez3D-I™ (VATECH Co., Ltd., Korea), which manages image acquisition and reconstruction. The field of view of this machine is 100 mm in diameter and 85 mm in height, and the exposure parameters were 94 kVp and 7.4mA. Low-dose mode was selected with a voxel size of 0.2 mm, which gave enough spatial resolution for our study. The DICOM data obtained from this exposure was used to assess the spatial position of the molar with the fixed coordinates of the reference cubes in terms of mesiodistal inclination, buccolingual inclination, and mesiodistal and apicogingival. The furcation point and the long axis of the tooth were used to make these calculations. (Figure 3)

Duplication of the typodont

After carefully inspecting the CBCT of the first typodont and confirming that the tooth lay on the same plane as the reference point, we started the process of making a new typodont. A new scan of the first typodont was obtained using the same scanner that was mentioned earlier. Using this scan, a rigid guide was created to precisely place the tooth in the same spatial location in the new typodonts. Additionally, the clear aligners were made using this same scan. (Figure 4:A)

The OBJ file was imported into the RealGUIDE™ software version 5.4 (3DIEMME S.r.l., Italy) program, where two guides were designed with different paths of insertion: one from the mesio-buccal direction and the other from the disto-lingual direction. This two-guide method makes sure that the teeth are in the right place with great accuracy and stability. (Figure 4:B)

The STL files of the guides were imported and printed using the MicroForm™ software (Microlay S.L., Spain) with Dentona® Surgical Guide Resin (Dentona GmbH, Dortmund, Germany) on the Microlay® Versus 365™ printer (Microlay S.L., Spain), configured at a 100-micron layer thickness[17]. (Figure 4:C)

After printing, the guides were washed in 96% ethanol for 3 minutes for two cycles using the Anycubic™ wash and cure (Anycubic Technology Co., Ltd., Shenzhen, China) to remove excess resin. They were then post-cured in the same machine for 10 minutes to ensure complete polymerization and eliminate any residual monomers. Using the KeyModel resin and Microlay printer, 14 additional typodonts were printed. With the aid of the surgical guide, the tooth was accurately positioned in each new typodont, replicating the spatial position of the tooth in the original model. New CBCT scans had been taken of the new typodont to make sure that the teeth were in the same place as they were in the original one. (Figure 4:D)

Making Clear Aligners

The same scan used for surgical guide fabrication was imported into Maestro 3D™ software version 5.1 (AGE Solutions, Italy) to design a series of clear aligners incorporating various attachment geometries. During the base detection process, the supporting box was removed to facilitate the thermoforming process. This adjustment was necessary to eliminate a large undercut adjacent to the tooth, which could adversely affect the adaptation and fit of the thermoformed aligner sheets.

In the virtual setup, the mandibular second molar was initially inclined at 30° relative to a reference line parallel to the occlusal plane. The treatment aim was to reduce the inclination from 30° to 5° with the occlusal plane because, according to Andrews' Six Keys of Occlusion, the gingival portion of the tooth is distal to the occlusal portion[18]. The treatment plan required a total uprighting of 25°. The software automatically segmented this movement into 10 stages, each corresponding to a 2.5° increment per aligner.

Five distinct series of aligners were developed, each featuring a different attachment configuration:

1- Control group—no attachment. (Figure 5A&5B)

2- Horizontal rectangular attachment—A single attachment measuring 3 × 2 × 1 mm (length × height × thickness)[19]. (Figure 5C&5D)

3- Alternative twin horizontal attachments—The same horizontal rectangular attachment was divided into two equal parts and spaced 3 mm apart[19]. (Figure 5E&5F).

4- Vertical twin attachments—Two vertical rectangular attachments, each measuring 2 × 3 × 1 mm [20]. (Figure 5G&5H)

5- Inclined attachment—A single rectangular attachment (3 × 2 × 1 mm) placed at a 45° angle to the occlusal plane[21]. (Figure 5I&5J)

Each series of aligners was printed in triplicate (n = 3) to establish sample size. [12] KeyModel resin (Keystone® Industries, USA) was used in conjunction with the Microlay Microlay® Versus 365™ printer, configured to a 100 µm layer thickness. Post-processing followed the same protocol previously described: washing in 96% ethanol for two cycles of 3 minutes using an Anycubic[tm] washer, followed by curing for 10 minutes in the Anycubic[tm] UV chamber[22].

Thermoforming was conducted using CA® Clear Aligner sheets (Scheu-Dental GmbH, Germany) and a Biostar® IV thermoforming unit. The Scheu company recommends using 30s of heating and then 60s of cooling with the initial temperature to achieve the best fitness of the aligner on the 3D-printed models. Then manual trimming and polishing were done on the thermoformed aligners about 2 mm below the gingival line to enhance retention of aligners on the models during the study[23].

Using the Aligners

Maestro 3D™ software (AGE Solutions, Italy) labels the first aligner as the template aligner (T1), which helps to place the attachments on the typodont. After checking the proper fitness of the template on the typodont, a separating medium was applied to the inner surface of the template to facilitate the removal of the template after cutting the attachment composite similarly to protocols in indirect bonding procedures[24]. At the same time, acid etch and bonding were applied to the tooth surface. The attachment cavity within the template was then filled with a PALFIQUE LX5™ (Tokuyama Dental Corp., Japan)[21]. The template was used to transfer the uncured composite onto the typodont, where a curing light was used to cure the material.

Following attachment placement, Aligner No. 1 was fitted onto the typodont. The assembly was then immersed in a water bath at 50°C for 90 seconds, as recommended by the manufacturer of the typodont wax, to allow controlled tooth movement. After immersion, the typodont was removed from the bath and left at room temperature for five minutes to allow for cooling and stabilization of the wax. This thermal cycle was repeated for each subsequent aligner in the series. After application of aligners, a new CBCT was taken to evaluate the movements and new position of the tooth with the reference points.

Statistical Analysis

Data analysis was performed using SPSS® version 25 (IBM Corp., Armonk, NY, USA). Group differences were assessed using the Kruskal–Wallis test, followed by Dunn's post hoc test with Bonferroni correction. Statistical significance was set at $p \leq 0.05$.

Results

For mesiodistal inclination changes, all groups showed different amounts of uprighting capacity, reflecting the attachment geometry. The pretreatment angle between the long axis of the tooth and the reference plane was 60°. The inclined attachment demonstrated the most pronounced effect, 79.5° (78.4°-80°), as in figure 6A, followed by the single horizontal 74.1° (73.2°-74.8°), alternative twin 68.8° (68.4°-69.2°), and twin vertical 64.9° (64.6°-66.1°) groups. The group without attachments, also known as control group, showed least increase, 66.1° (65.7°-66.4°). A Kruskal–Wallis test was done and showed significant difference among groups statistically ($H = 14.03$, $p = 0.015$). Then, a post hoc test was done and revealed that the inclined group was significantly different statistically from the control (adjusted $p = 0.026$), suggesting that this attachment geometry was the most effective in mesiodistal uprighting (see table 1).

For buccolingual inclination, the single horizontal 87.4° (86.4°-88°), inclined 89.5° (86.7°-89.6°), and no-attachment 86.7° (86.3°-87.1°) groups remained close to baseline, whereas the alternative twin 78.2° (75.7°-81.7°), as in figure 6B, and twin vertical 76.1° (74.7°-77.7°) groups exhibited greater buccal tipping. The overall Kruskal–Wallis test showed a significant difference between groups ($H = 10.57$, $p = 0.032$), suggesting that twin-type attachments might cause more unwanted movement of the teeth from side to side (see table 1).

Regarding vertical distance, the alternative twin group showed the largest reduction among all the groups 12.3 (12.1-12.4 mm), while the inclined attachment 13 (12.9-13.1 mm), single horizontal 13(12.9-13.35 mm), twin vertical 13 (12.85-13.1 mm), and no-attachment 13.13 (12.9-13.35 mm) groups showed moderate change as in figure 6C.

But the Kruskal–Wallis test showed no significant differences among groups ($H = 7.51$, $p = 0.111$) (see table 1).

In terms of mesiodistal distance, the pre-treatment baseline was 15.60 mm. The inclined attachment13.6 (13.4-13.7 mm) and single horizontal 13.73 (13.3-13.8 mm) groups showed the greatest reductions, while the twin vertical 15.27 (15.1-15.5 mm) and alternative twin 14.8 (14.75-15 mm) groups maintained values closer to baseline. The control group showed a mean of 15.07 (15-15.15mm) as in figure 6D. The Kruskal–Wallis test revealed a significant difference across groups ($H = 11.39$, $p = 0.023$), although no pairwise comparison remained statistically significant after Bonferroni adjustment (see table 1).

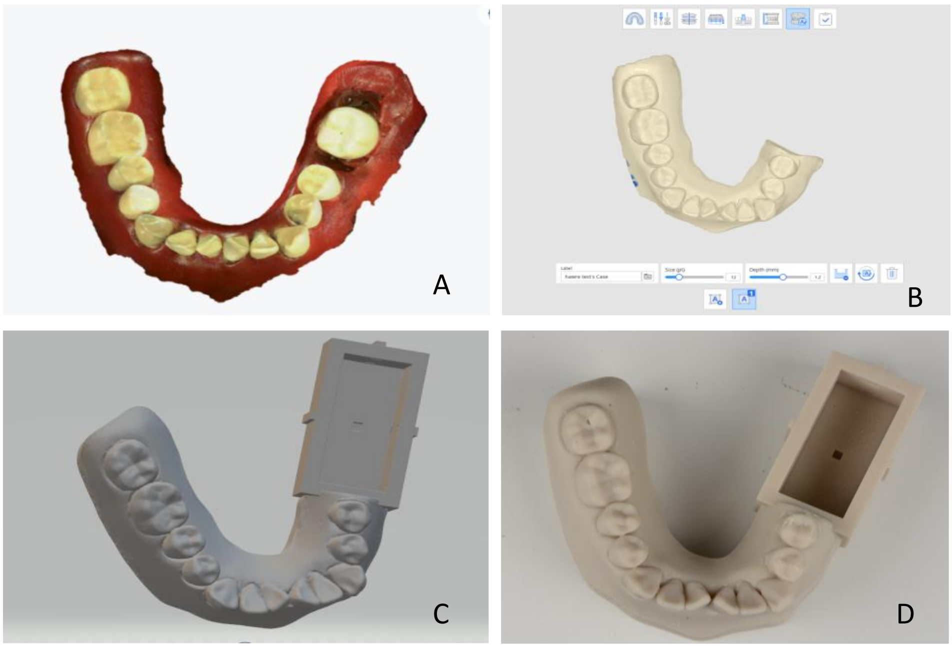

Figure 1: A: First scan of the standard typodont, B: Using Medit model builder to create a model with removing the lower left molar region, C: Virtual typodont after adding supporting box, D: First physical model.

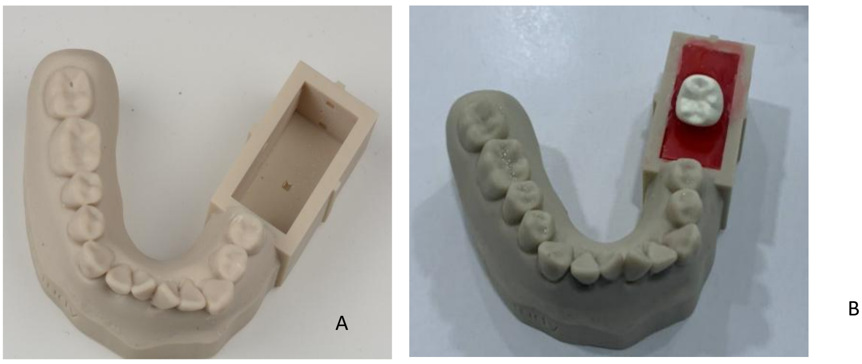

Figure 2: A: Physical model after filling the small cubes with flowable composite, B: Physical model after adding typodont wax and aluminum-based tooth.

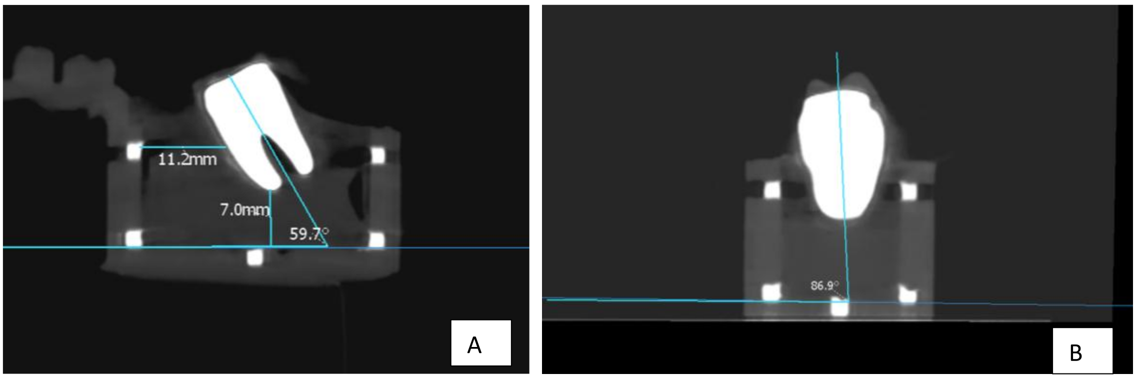

Figure 3: Initial records from CBCT A: Sagittal plane, B: Coronal plane.

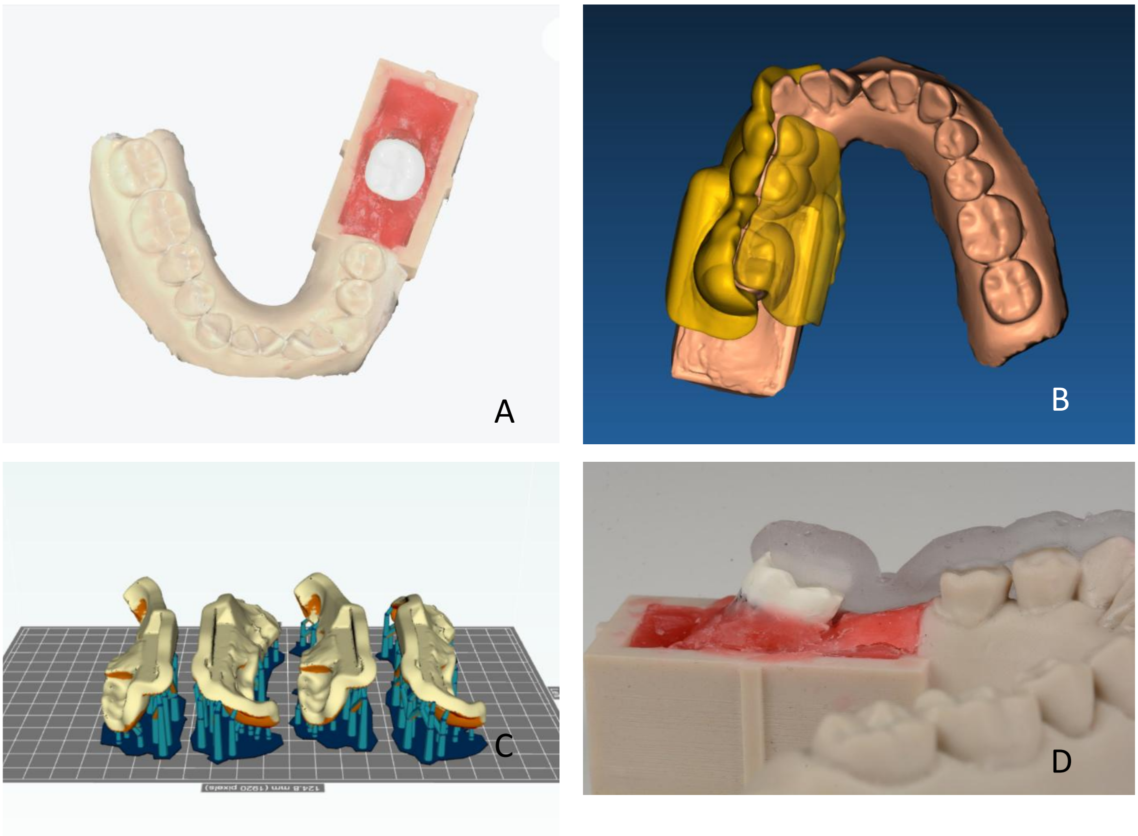

Figure 4: A: OBJ file of first typodont B: Virtual design of guides in REALguide C: Guides ready for print D: Tooth has been placed with help of surgical guide.

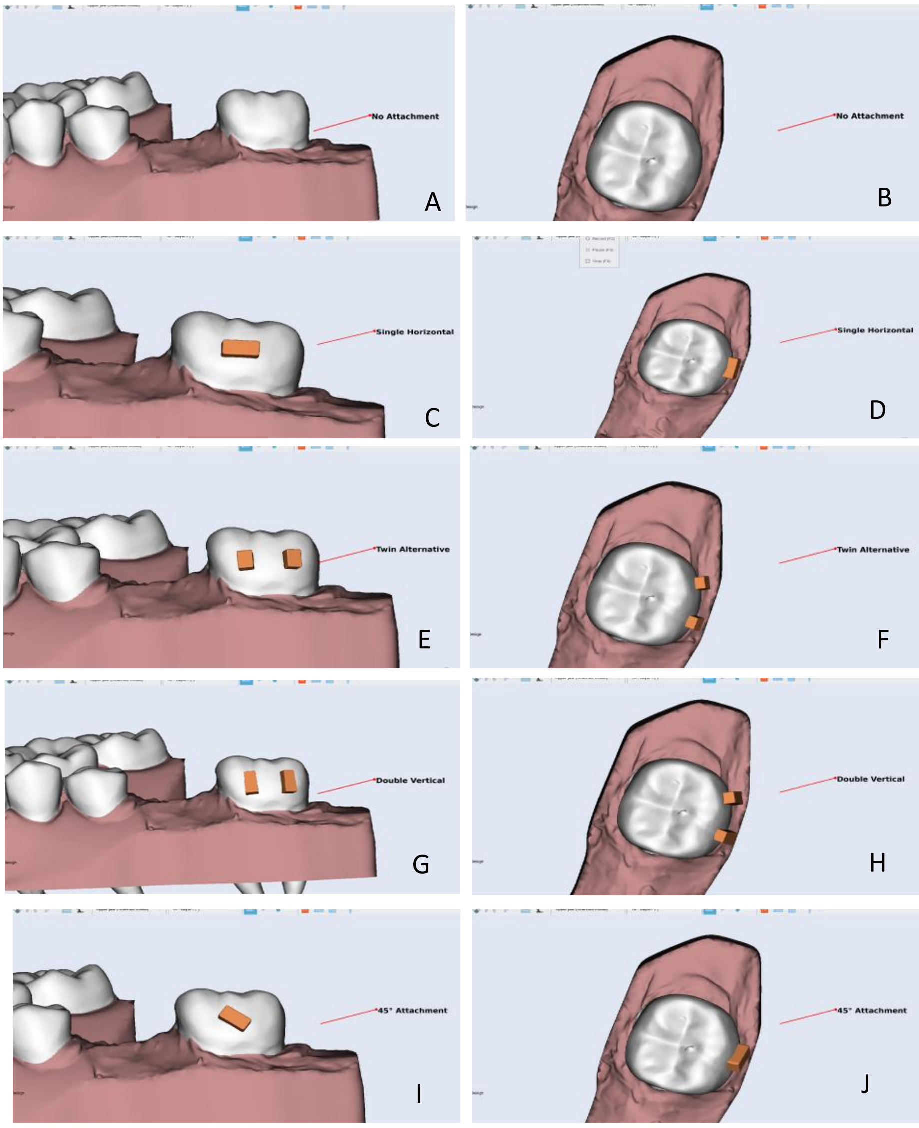

Figure 4: A: Without attachment buccal view, B: Without attachment occlusal view, C: Single horizontal buccal view, D: Single horizontal occlusal view, E: Alternative twin attachments buccal view, F: Alternative twin attachments occlusal view, G: Vertical twin attachments buccal view, H: Vertical twin attachments occlusal view, I: Inclined attachment at 45° to occlusal surface buccal view, L: Inclined attachment at 45° to occlusal surface occlusal view.

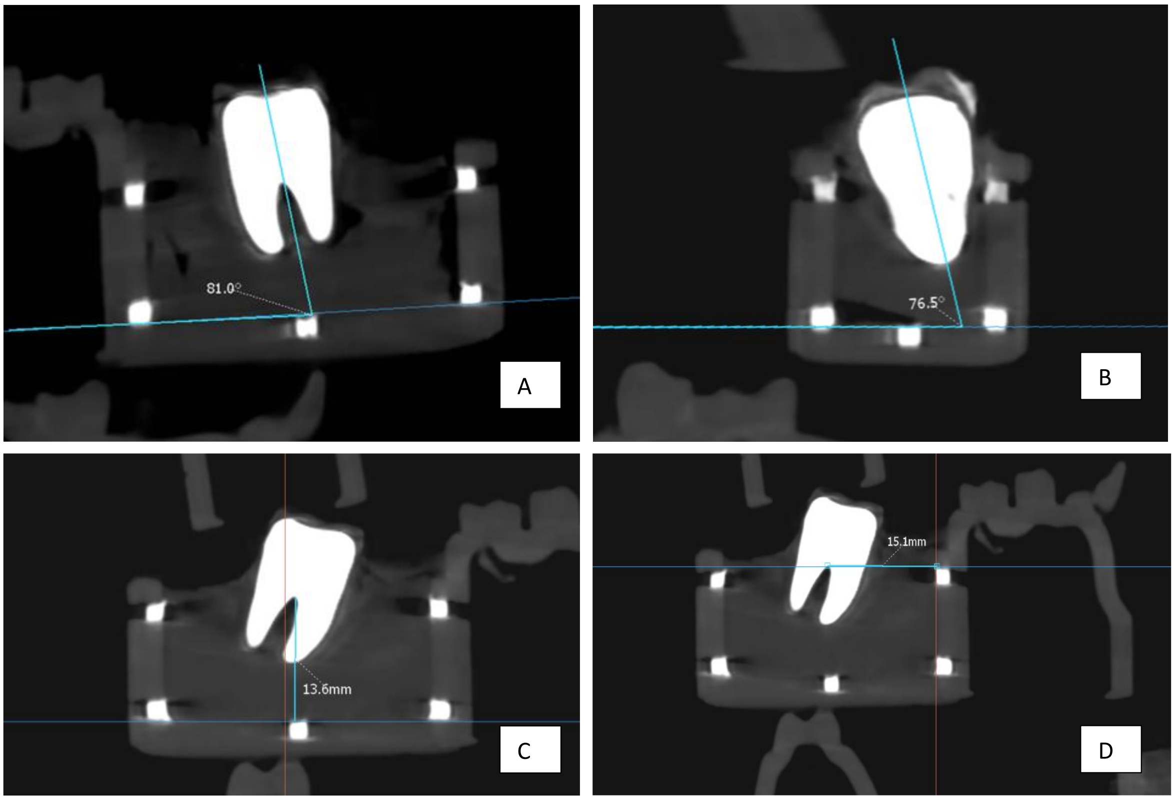

Figure 5: A: Change in mesiodistal inclination by using single oblique rectangular attachment, B: Change in buccolingual inclination by using twin alternative attachment, C: Change in vertical distance in control group(without attachment), D: Change in mesiodistal distance in control group (without attachment).

Table 1: Average change in tooth position.

Type of attachment	Change in Mesiodistal inclination		Change in buccolingual inclination		Change in vertical distance		Change in mesio-distal distance	
	Post-test readings	Average change	Post-test readings	Average change	Post-test readings	Average change	Post-test readings	Average change
No attachment	66°	6°	86.7°	0.2°	13.13 mm	1.47 mm	15.07 mm	0.53 mm
Single horizontal rectangle	74°	14°	87.1°	-0.2°	13.00 mm	1.6 mm	13.73 mm	1.87 mm
Inclined attachment	79°	19°	87.9°	-1°	13.27 mm	1.33 mm	13.60 mm	2 mm
Twin alternative	68.8°	8.8°	78.2°	8.7°	12.30 mm	2.3 mm	14.87 mm	0.73 mm
Two vertical rectangular attachments	65.4°	5.4°	76.2°	10.7°	13.00 mm	1.6 mm	15.27 mm	0.33 mm

Discussion

This in vitro study looked into how varied attachment geometries affected the uprighting of second molars in clear aligner therapy. Even though our study has its own limitations, the study showed that simple attachment geometries like single horizontal rectangular and single inclined at 45 degrees to the occlusal plane can act better as compared to complex geometries like alternative twin and double vertical attachments. The findings from the study can help orthodontists and clear aligner technicians to select simple and effective attachments during planning.

The results of this in vitro study showed that single attachments were achieving better results in terms of uprighting a tilted lower second molar as compared to other attachment configurations, like twin vertical and twin horizontal attachments, as well as the control group without attachments. This result shows that the presence of attachments, as well as their shape and direction, are crucial factors in determining how well force is transmitted through clear aligners[21].

One of the reasons why single attachments work better is that they are easier to make and are more likely to contact the aligner material during treatment. A single horizontal attachment gives the force system a wide, uniform surface that makes sure it always makes contact with the aligner. This makes the force system more predictable[25]. Also, a single inclined attachment at 45 degrees to the occlusal plane can make a vector of force that facilitates the efficiency of the attachment to an upright tilted molar by combining horizontal and vertical force components[26].

The less useful twin attachment designs, on the other hand, may be due to several things that affect each other. Constructed complex object shapes like twin attachments are more likely to be inaccurate during the 3D printing and thermoforming steps. Even a small deviation in the attachment's size or location can have a large effect on how well it fits and the direction of force[27]. This is important because thermoforming at high temperatures can cause small changes in the shape and thickness of the material. These small changes in the attachment position and the planned position can add up over the course of treatment and cause a clinically significant error, which leads to poor performance of the attachments[28].

Furthermore, when placing composites, templates with two attachment cavities may not seat properly because they are more rigid or have undercut areas. This makes it harder to make sure that the template fully adapts to the orthodontic appliance or natural teeth. As a result of incomplete seating, attachments may move or become distorted, which makes their effective engagement with the aligner even worse. On the other hand, single attachments are easier to seat correctly because there is less chance of template rocking or incomplete adaptation[29].

From the point of view of biomechanics, single attachments may also make vector distribution simpler. When two attachments are used together, they might create opposing force vectors that hide the original purpose of the vectors at the same time. Twin attachments can also induce torque and moments that tilt the tooth lingually. This could weaken the effective moment arm needed to straighten a tilted molar or lead to off-axis moves that make the force system less effective[26].

In the end, how well the attachment composite and aligner material work together depends on the properties and limitations of both materials. For example, if the attachment composite does not cure properly or bond well to the tooth, it may lead to inaccuracy of fitting and transmitting correct vector of force. In this study, although a nano-hybrid composite (PALFIQUE LX5) was used, even with its outstanding strength, it still can be affected by the angle and strength of the curing light, which make it harder to control when attachments are more complex[27].

Additionally, the thermoforming process itself can be a source of issues affecting the reliability of complex attachment geometries. During this process a heated aligner material is molded onto the 3D-printed models. Complex or large attachments require the thermoplastic to stretch further and conform more to replicate the attachment shape[28]. However, this increased deformation introduces multiple risks. First, the material reduces in thickness, and this localized thinning can reduce the mechanical stiffness of the aligner in critical zones[30]. Second, the sharper the attachment design, the more likely it is to cause material bridging, a phenomenon where the aligner fails to contact the attachment surface fully, creating a void or a gap[31]. Third, increased surface complexity may result in variability in heating and cooling rates across the sheet during thermoforming, which can induce internal stresses and micro-deformations in the material. All these features make it harder for the aligner to fit well with complicated shapes, especially when compared to simpler shapes like single horizontal or inclined attachments. In both clinical and experimental situations, even minor errors in thermoforming can lead to accumulated inaccuracies in tooth movement, which consequently affects the overall efficacy and predictability of the treatment.

The findings of this study are comparable to those reported in previous research and are consistent with the existing literature[17]. This agreement supports the reliability of the results and indicates that the outcomes are in line with established evidence.

Conclusion

The efficiency of different attachment geometries on uprighting the second molar with clear aligner treatment was assessed using four outcome measures: mesiodistal inclination, buccolingual inclination, vertical distance, and mesiodistal distance. This study supports the idea that simpler attachment shapes are not only easier to make but also more effective in clinical use, as they help apply force more consistently. To better understand these effects, future research could use finite element analysis or in vivo studies to explore how attachment shapes influence molar uprighting in real clinical settings.

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