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Original Article

Effects of different aligner materials and attachments on orthodontic behavior

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Abstract *Background/purpose:* The orthodontic aligner becomes popular worldwide in orthodontic therapy as an esthetic alternative to fixed labial braces. This study evaluated orthodontic tooth movement behavior using different aligner materials and attachment shapes for the movement of a single tooth.
Materials and methods: First bicuspid extracted resin typodont models were printed with a 3D printer. Three type of attachments, an ellipsoid shape (thick and thin) and a bar, were designed to fit the canine crown surface. Three types of aligner materials, Polyethylene Terephthalate enhanced with glycol (BIOSTAR) Polyethylene Terephthalate (BenQ), and Thermoplastic polyurethanes (TPU) were used to fabricate different aligners. The typodonts with aligners were sunk in a water bath to simulate canine distal movement *in vivo*. The canine crown, root movement, and long axis angle changes in each step were calculated and recorded. The data were analysed using a oneway ANOVA statistical method.
Results: Comparing the three aligners, the changes the long axis of the canine showed that the BENQ group had a smaller change in the long axis angle. The BENQ group canine involved bodily movement, but the canine movement of the BIOSTAR and TPU group involved tipping. Comparing the three attachments, the bar type attachment had more canine crown tipping in the BIOSTAR and TPU groups. The thick and thin ellipsoid-shaped attachments showed no statistical differences in tooth movement.
Conclusion: Attachment shape or size had little influence on the bodily movement of the tooth. A high modulus material may thus be suitable for clinical applications.

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Introduction

Digital dentistry has arrived and now covers all fields of dental treatment. In particular, digitally aligned orthodontic treatment can be performed by orthodontists or general dentists. For the sake of the esthetic demands by patients, it has become popular worldwide in orthodontic therapy as an esthetic alternative to fixed labial braces.[1] The aligner is highly accepted by most of the treatment population except patients with allergic reactions.

Numerous aligner companies have appeared in the market with similar treatment philosophies. The thermoplastic materials used by aligner manufacturers currently include polyethylene terephthalate glycol-modified (PET-G), polypropylene, polycarbonate (PC), thermoplastic polyurethanes (TPU), ethylene vinyl acetate, etc.[2] Materials should be transparent, have a low degree of hardness, good elasticity, high resilience, and should be biocompatible and effective in terms of correcting tooth positions.[3] The most important aspects are comfort and aesthetics.

Aligner performance is strongly influenced by the material construction. In the early hours of wearing an aligner, 50% of the initial stress value can be released. After 24 h, orthodontic loads on the aligner and changes in stress influence the programed tooth movement.[4] Although aligner material compositions are different, the thickness of the plates range from 0.5 mm to 1. 5 mm.[5] The thickness of the material can affect the biomechanical properties associated with tooth movement. Among the different aligner materials, thick materials deliver higher forces than those made from thin materials.[6,7]

It is difficult to correct tooth torque and rotation through the use of an aligner treatment.[8] Attachments have been designed to apply force systems to teeth. The different attachment shapes are designed to enhance retention and facilitate complex orthodontic tooth movement. Optimized attachment shapes are increasing in complexity and are proving to be clinically better in terms of controlling tooth movements.[9] The use of beveled attachments increases retention significantly, but ellipsoid attachments have been found to have no significant effects on retention.[10]

Thermoplastic materials on the market have very different mechanical characteristics. A 0.75-mm thick single-layer materials stress relaxation study, where assays showed that PETG materials led to a higher velocity of stress relaxation (62% in 24 h) as compared to other materials. The TPU material started with very low initial stress values. The present study was aimed toward examining the behavior of orthodontic aligners during the entire course of treatment. The variables include various aligner materials combined with various attachments of different shapes.

Material and methods

Testing model setup

The typodont had standard metal aligned teeth (mandible first molar, second bicuspid, canine, and later incisor) seeded in typodont wax (Fig. 1). The wax pattern including the teeth was impressed and transferred to a stone model. After the stone model was set, it was scanned with a 3 Shape Trios oral scanner (3 shape Co. Copenhagen, Denmark). The canine tooth was extracted using the 3Shape Ortho system software. A supporting box (w: 15.8 mm, L: 43.3 mm, H: 41.2 mm) was added as a typodont stent, which allowed the canine and first bicuspid spaces to be empty in the software (Fig. 2).

Attachment designs and teeth alignment

The attachments used in present study included a thin ellipsoid shape (w: 1 mm, L: 3 mm, H: 0.75 mm), a thick ellipsoid shape (w: 3 mm, L: 1 mm, H: 1 mm), and a bar shape (w: 1 mm, L: 5 mm, H: 1 mm) (Fig. 1). The attachments were added to the canine labial surface using the software. Then, the original testing resin models with and without attachments were printed out using the FORM 2 (Form Lab. Somerville, MA. USA) SLA 3D laser printer (Figs. 3 and 4).

The mandible metal canines were placed into the above referenced 3D printed resin typodont and the empty spaces were filled with typodont wax (Fig. 3). A silicone impression material (Aquasil soft putty, Dentsply Co. Charlotte, NC, USA) was used to register the tooth position at the initial starting point. The register recording each test was set at the same start point. The first bicuspid was set to leave a 7 mm space. The typodont was scanned again. The data was manipulated using 3 Shape Ortho analyzer software to simulate the canine distal movement. The amount of canine distal movement at each step was set to 0.25 mm changes. A total of 28 sets of resin block working models were printed out using the Form 2 SLA printer.

The aligner fabrication

The aligners materials used in the present study included Duran (Scheu Dental GmbH Co., Iserlohn, Germany [abbreviation BIOSTAR], EasyDu (BenQ Co., Taipei, Taiwan [abbreviation BENQ]), and MaxFlex™ Coping sheet (MaxFlex Co., Taipei, Taiwan [abbreviation TPU]) (Table 1). The aligners were vacuum-thermoformed using the Biostar VI apparatus (Scheu-Dental, Germany). After separation from the working model, the gingival margins of the aligners were cut to the respective 2 mm gingival widths and then were trimmed and smoothed.

Tooth movement simulation recording and movement calculation

The wearing aligner working model was placed into a 56 °C water bath for 90 s and then cooled in cold water for 90 s. The metal wire was prepared and embedded into a plastic sheet, where the metal wire was coordinated with the long axis of the tooth in the working model. The cooled working model was covered with a metal wire plastic sheet to take an X-ray. The radiation time was set 0.14 s. The above steps were repeated until the space was closed.

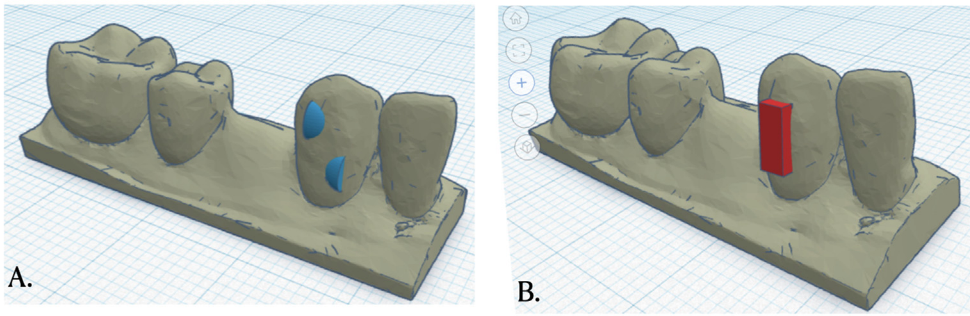

Figure 1 The two shape attachments (bar type and ellipsoid type) placed on the labial surface of the canine.

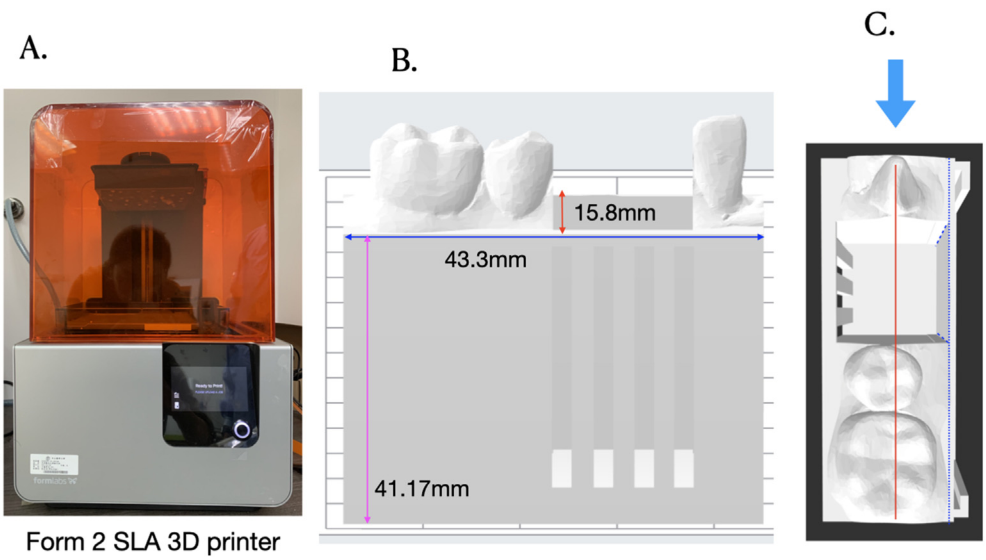

Figure 2 A. The 3 Shape 3D printer. B. The 3D printed resin typodont model. C. View from the occlusal surface.

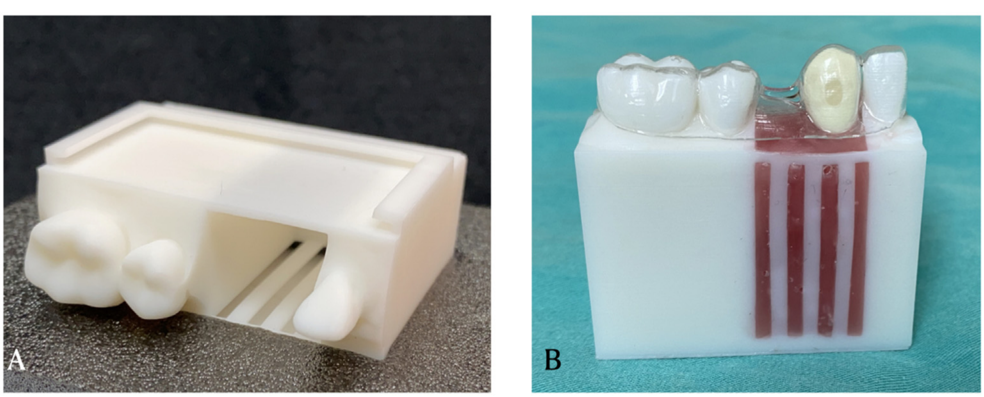

Figure 3 A. The printed resin typodont model. B. The typodont with a movable metal canine tooth inserted. The clinical surface of the teeth covered with an aligner.

The tooth movement measurement points were recorded at the crown, root, and long axis of the canine on the X-ray film (Fig. 5). Each aligner was tested in triplicate. The data comparison included crown movement (mm), root movement (mm), and changes in the canine long axis (degrees). The data were analyzed using a one way ANOVA. All statistical tests were performed, with significance set at $p < 0.05$.

Results

Comparing the canine tooth movement without attachments

There were no differences in the canine crown movement in the three types of materials (Fig. 6A). There was a linear

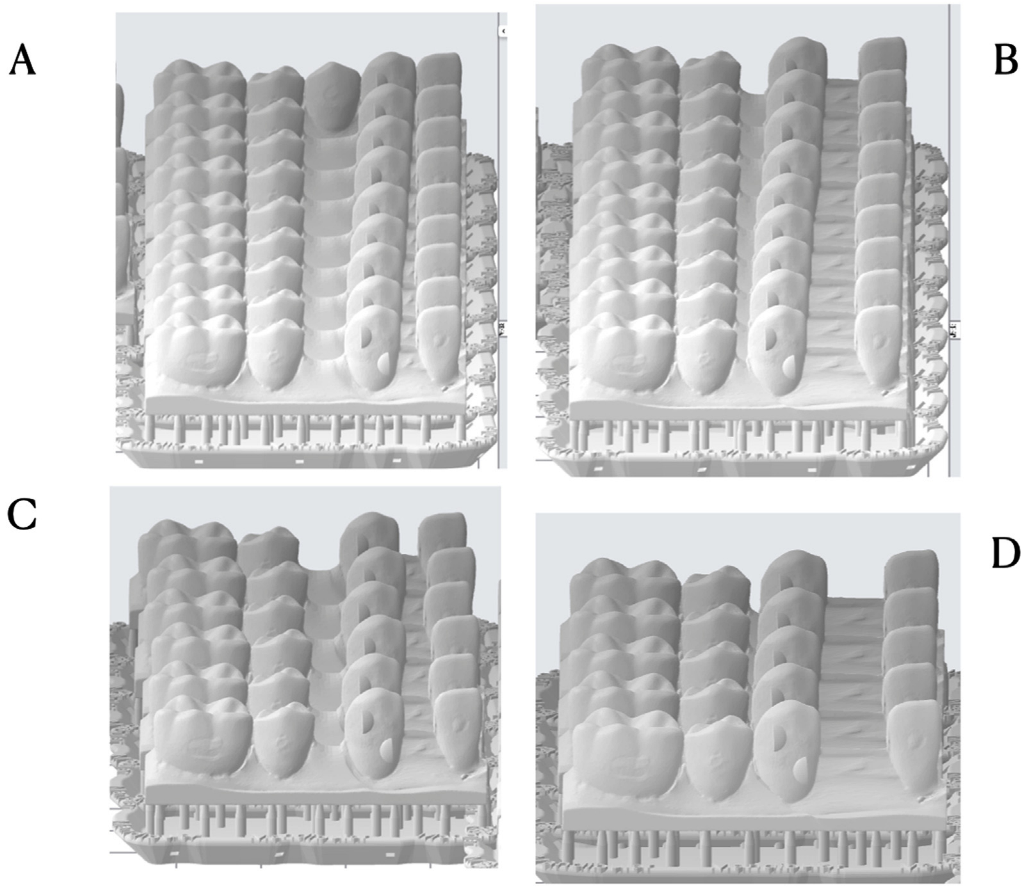

Figure 4 The 3D printed resin model showing all of the canine distal movement steps used for the aligner fabrication.

increase in the crown movement with the steps. The canine root movement in the BENQ group moved distally following the aligner steps. However, in the TPU and the BIOSTAR groups, the root stayed in the mesial region (Fig. 6B). The changes in the long axis of the canine indicated that the BENQ group had a smaller change in the long axis angle ($1.2^\circ \pm 0.8^\circ$, $p < 0.05$). The TPU and BIOSTAR groups had greater changes in the long axis angle, but there was no statistically significant difference between them ($p > 0.05$, Fig. 6C).

Comparing canine tooth movement with and without attachments

There was no statistical difference in the canine crown movement between the attachment group and the group without attachments ($p > 0.05$, Fig. 7A). There was a linear increase in the crown movement with the aligner steps. There was no statistical difference between the bar and ellipsoid-shaped attachments in terms of crown movement ($p > 0.05$). The canine root movement in the groups with and without attachments demonstrated a statistically significant difference ($p < 0.05$). The thin ellipsoid-shaped attachment group showed less root mesial position than the thick type and bar type attachment groups after step 5 ($p < 0.05$ Fig. 7B).The changes in canine long axis angle showed that the bar type attachment group ($27^\circ \pm 0.9^\circ$) had larger measurements than the group without attachments ($26.3^\circ \pm 0.9^\circ$, $p < 0.05$). A comparison between the ellipsoid-shaped (thin: $25.5 \pm 0.3^\circ$; thick: 26.1 ± 0.7^0) attachment group and the group without attachments showed no statistically significant difference in the long axis angle of the canine ($p > 0.05$, Fig. 7C).

Table 1 The three types of aligner materials.

Brand	Composition	Thickness (mm)	Heating time (s)	Cooling time (s)
Duran (Scheu Dental, Iserlohn, Germany)	PETG	0.75	30	20
EasyDU (BenQ Co, Taipei, Taiwan)	PET (PFb/PFc)	0.75	20	20
MaxFlex™ coping sheet Maxflex Co, Taipei, Taiwan)	TPU	0.76	25	20

PETG:Polyethylene Terephthalate (PET) -glycol (G), test code: BIOSTAR
PET:Polyethylene Terephthalate, test code: BENQ.
TPU:Thermoplastic polyurethanes, test code: TPU.

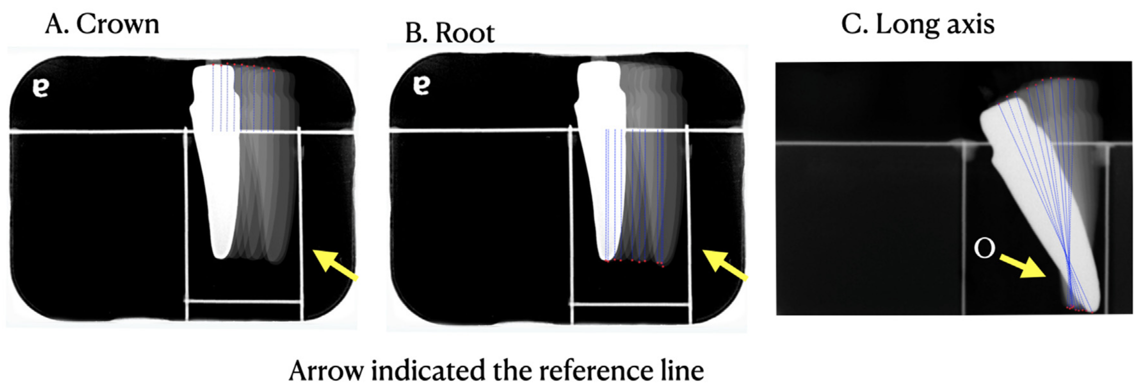

Figure 5 The canine movement measurement using superimposition of an X-ray. A. The crown measurement was performed by drawing a vertical line from the clinical crown midline to the reference line. B. The root measurement was performed by drawing a vertical line from the root midline to the reference line. C. The changes in the long axis were determine by defining 1/3 of the apex as center O. The change in the long axis was performed by measuring the angle of the long axis relative to the original long axis line.

There were no statistically significant differences in the canine crown movement for either the attachment groups or the groups without attachments ($p > 0.05$, Fig. 7D). There was a linear increase in the crown movement with aligner steps. The bar and ellipsoid-shaped attachments showed no statistically significant differences in terms of crown movement ($p > 0.05$). The canine root movement measurement with or without attachments group showed a statistically significant difference ($p < 0.05$). The bar type attachment group exhibited more root tip than the other group ($p < 0.05$). The thin ellipsoid-shaped attachment group showed less root tip than the other groups ($p < 0.05$, Fig. 7E). The changes in canine long axis angle showed that the bar type attachment group ($27^\circ \pm 0.5^\circ$) had larger measurements than the group without attachments ($24.7^\circ \pm 1^\circ$) ($p < 0.05$). A comparison of the TPU aligner for the ellipsoid-shaped (thin: $23.8 \pm 1^\circ$; thick: 24.7 ± 0.8^0) attachment group and the group with no attachment showed no statistically significant difference ($p > 0.05$, Fig. 7F).

Comparison of the various aligner attachments

In the thin attachment comparison, the BIOSTAR and TPU groups showed no statistically significant difference in terms of the long axis movement ($p > 0.05$, Fig. 8A). In the thick attachment comparison, the BIOSTAR and TPU groups showed no statistically significant difference in terms of crown movement ($p > 0.05$), but there was a statistically significant difference in root movement after six steps ($p < 0.05$, Fig. 8B). The bar attachments applied on the BIOSTAR and TPU groups, in terms of both crown and root movement, showed no statistically significant differences ($p > 0.05$, Fig. 8C).

Discussion

The aligner tooth movement is accomplished by changing the aligner shape. Aligner discrepancies can create the pushing force necessary to move the tooth. This pushing

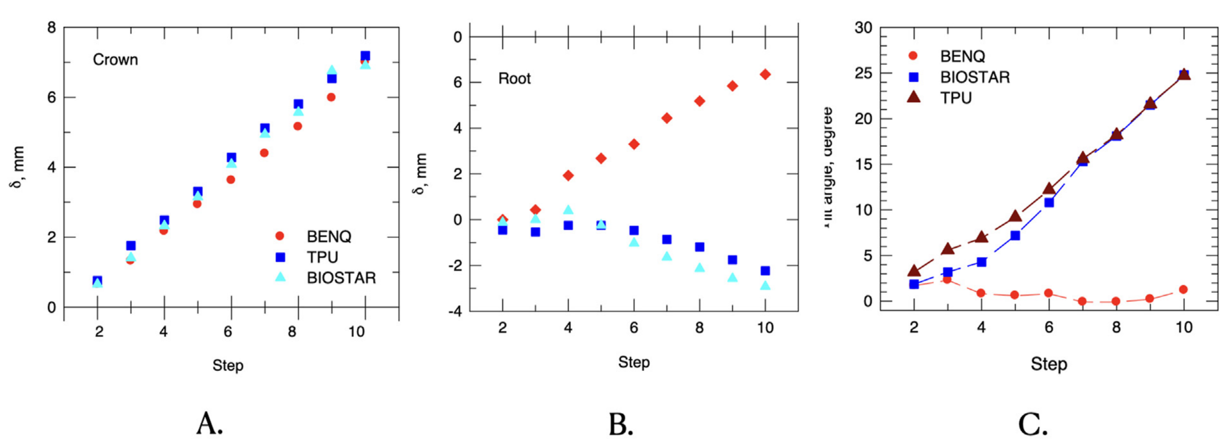

Figure 6 Comparing 3 types of aligner material in relation to tooth movement. This experiment shows no attachment on the tooth surface. A. Crown measurement. B. Root measurement. C. Long axis measurement. The BENQ group shows a smaller crown tip and larger distal root torque than that in the BIOSTAR and TPU groups.

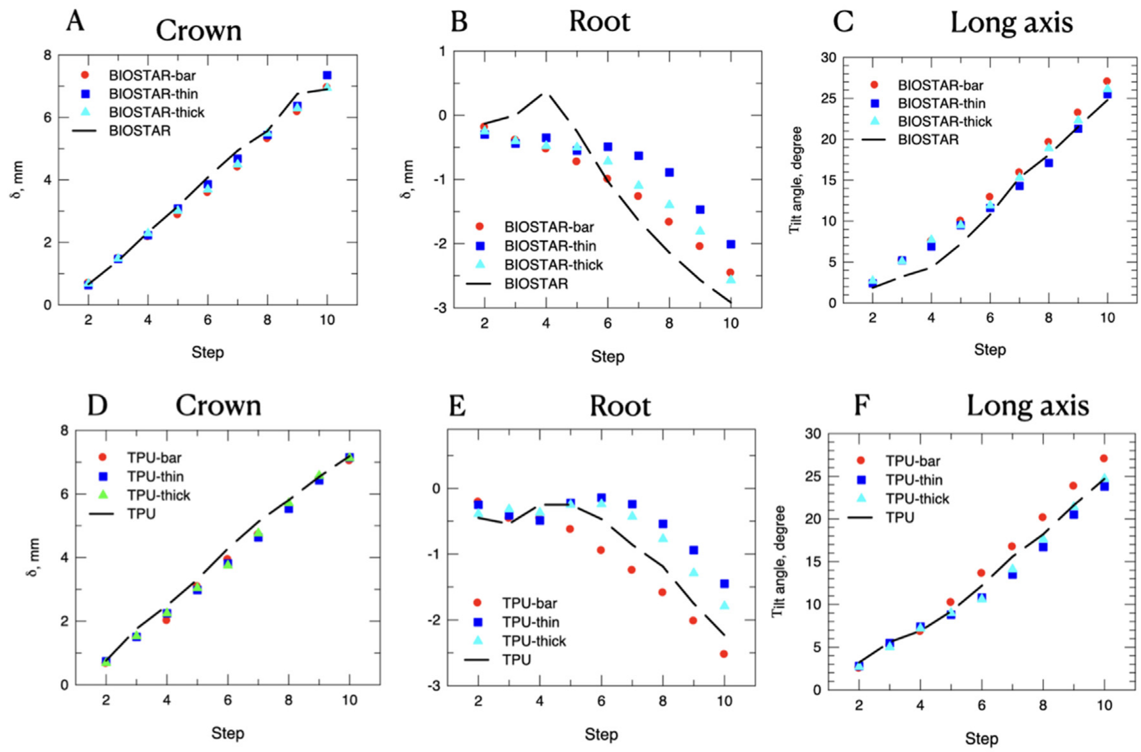

Figure 7 Comparison of tooth movement in BIOSTAR group with and without attachments. A. Crown measurement. B. Root measurement. C. Long axis measurement. The bar attachment group showed a larger mesial root torque than the ellipsoid attachment groups. Comparison of tooth movement in the TPU group with and without attachments. D. Crown measurement. E. Root measurement. F. Long axis measurement. The bar attachment group had a longer long axis angle than either the ellipsoid attachment groups or the group with no attachments.

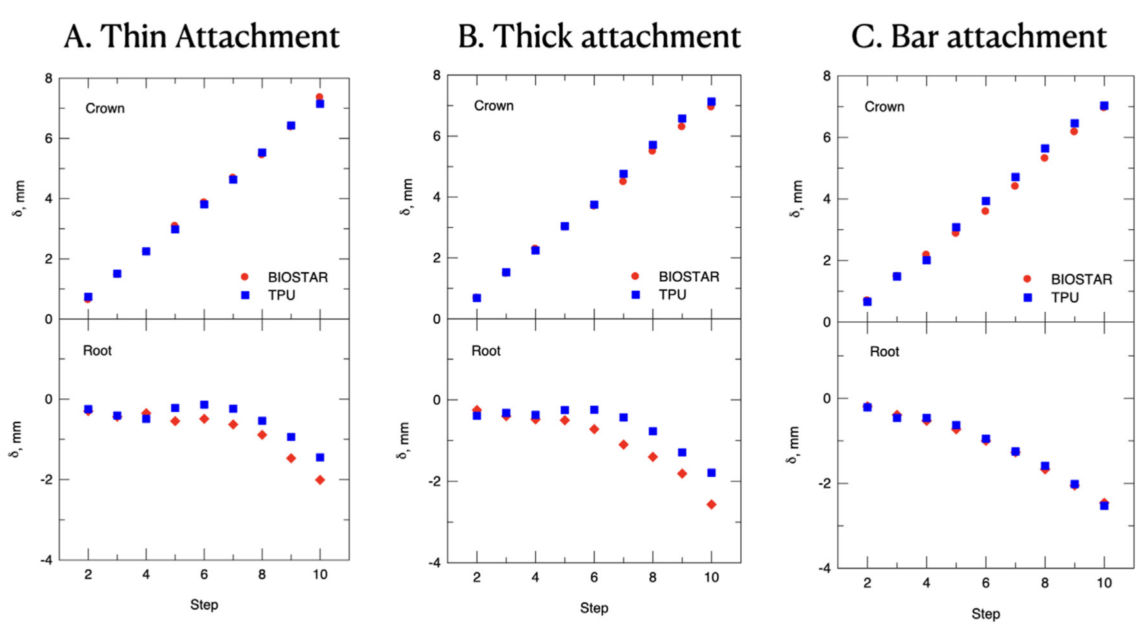

Figure 8 Comparison of the different types of attachments between the BIOSTAR and TPU groups. The ellipsoid attachment of the BIOSTAR group had a larger root mesial movement than the TPU group. The crown and root movement of the BIOSTAR and TPU groups showed no difference with the bar attachment on the tooth.

Table 2 The Young's modulus for the three types of aligner meterials.

Brand	BENQ	BIOSTAR	TPU
Young's modulus (E) $\times 10^6$ Pa	134	90	99

BIOSTAR: Duran (Scheu Dental GmbH Co., Iserlohn, Germany).
BenQ: EasyDu (BenQ Co., Taipei, Taiwan).
TPU: MaxFlex™ Coping sheet (MaxFlex Co., Taipei, Taiwan).

force acts on the clinical crown but not through the tooth center resistance. Thus, the aligner tooth movement always induces movement of the crown tip.

The Young's moduli of the BIOSTAR, TPU and BENQ groups were 90, 99 and 134 (x10^6 Pa), respectively (Table 2), where a higher the modulus of the material represented the less material deformation. The present study showed that the canine crowns in the BIOSTAR and TPU groups underwent distal crown tip movement (Fig. 9A and B). However, the BENQ group canine crown showed bodily movement (Fig. 9C). It is thus suggested that a BENQ aligner with a higher modulus can wrap the tooth tightly and increase aligner retention.

When the tooth is tipping, if the aligner material has a high degree of elasticity, the tooth can be rebound and upright. One may doubt the validity of the results of the present study, since the tests were conducted on a wax system and not under actual oral condition. However, when we reviewed the BIOSTAR and TPU results in this study, the canine underwent tipping movement and did not remain upright. This concurred with the clinical situation for the aligner (Fig. 6). Thus, we suggest that if the aligner modulus is high and can be retained in the mouth for a period of the, the tooth may undergo bodily movement.

To achieve better aligner retention, two factors need to be considered. One is the attachment shape and application, and the other is the aligner material selection. A well-defined geometric attachment is used to generate forces or movements, increasing the capacity of orthodontic aligners to move the tooth.[10] When beveled attachments are compared with ellipsoid attachments or no attachment models, a hard aligner material requires a greater amount of force to remove an aligner from a cast.[11] Retention depends on the material composition and does not necessarily correlate with the material thickness.[12] The present study used the same thickness of aligner material to evaluate the attachment shape on tooth movement effects. The aligner bar-shaped attachment led to more crown tipping in the present study.

The BIOSTAR and TPU group aligner with and without were compared to determine attachment effects on tooth movement. The tooth movement results for the BIOSTAR and TPU groups showed no differences based on attachment (Fig. 7). This may have been because the Young's moduli of the aligners used in the BIOSTAR or TPU groups were low, so the aligner couldn't withstand the tooth tipping stress, which in turn led to tooth tipping.

Two shape attachments, ellipsoid and bar shape, were used in present study. Two contour thicknesses were used for the ellipsoid attachment, one thin and one thick. The ellipsoid attachment was placed on the distal occlusal site and on the mesial gingival site of the canine crown (Fig. 1). It was designed to press against the distal tip of the crown. The bar attachment was designed as a long rectangular shape, one half of the clinical length, to react against the distal movement force causing root mesial tipping. The difference between the ellipsoid and bar shape was two points of contact and one big area of contact to act against the aligner pushing force.

The canine showed crown distal tipping and root mesial toque in the BIOSTAR or TPU group aligners with both

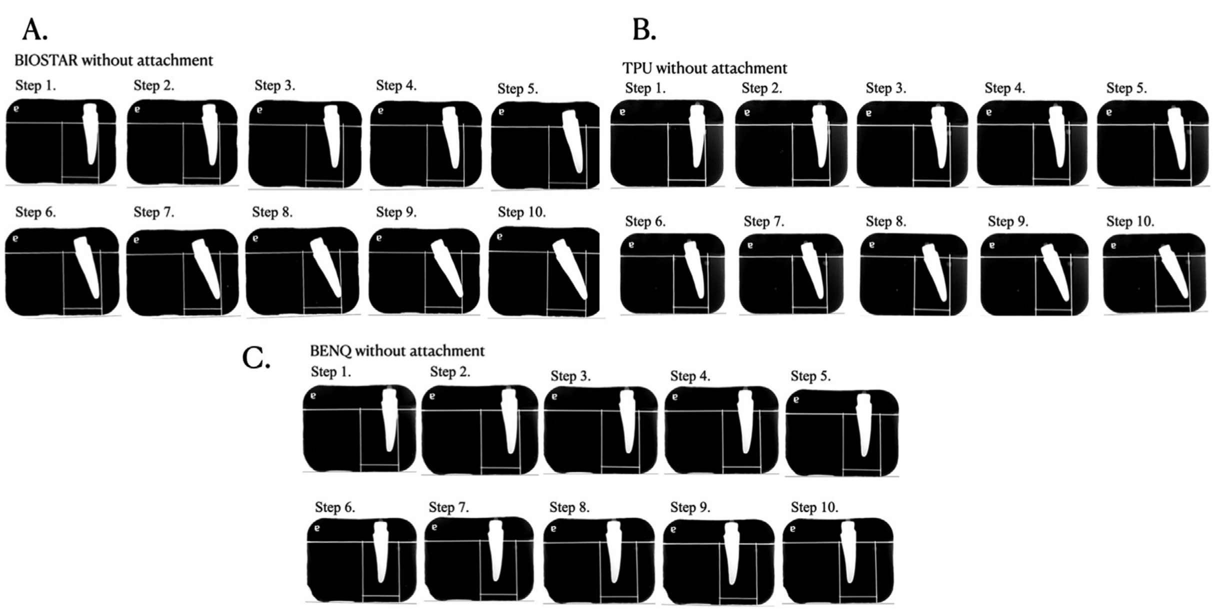

Figure 9 X-ray of aligner sequential tooth movement, with no attachment. A. BIOSTAR group. B. TPU groups. C. BENQ group.

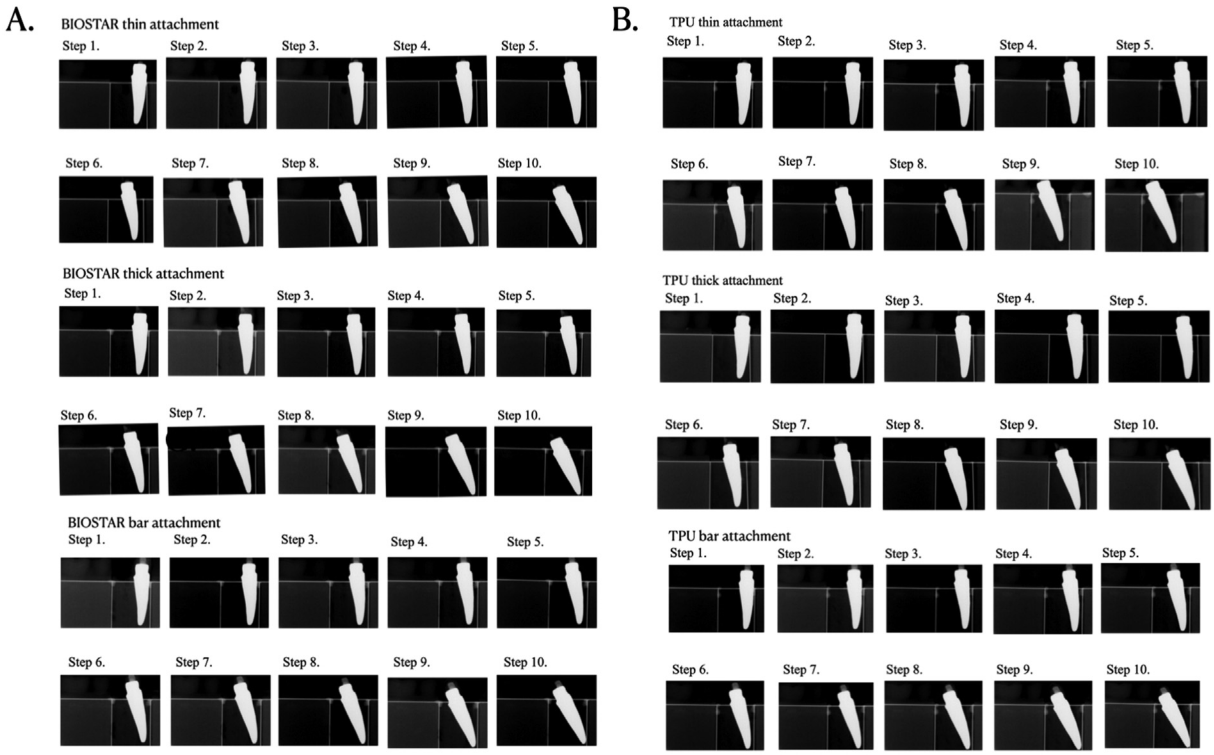

Figure 10 X-ray of aligner sequential tooth movement, with different attachments. A. BIOSTAR group. B. TPU groups.

ellipsoid- and bar-shaped attachments (Figs. 7 and 10). The BIOSTAR group showed that the bar type attachment caused a greater canine long axis angle than the ellipsoid attachment group. That is, more canine distal tipping occurred in the BIOSTAR bar attachment group. Using the thin or thick ellipsoid attachment on the BIOSTAR group canine led to tooth distal tipping but no statistically significant difference in the long axis angle of the canine (Figs. 7, 8 and 10). This indicated that ellipsoid- or bar-shaped attachment do not prevent crown tipping.

In the findings for the TPU group, the bar attachment exhibited larger measurements than the group with no attachment in terms on canine root movement and long axis angle measurements (Fig. 7). The canine root torque in the thin ellipsoid attachment group was less than that in thick ellipsoid attachment group (Figs. 8 and 10). To prevent canine distal tipping, the ellipsoid attachment was preferable to the bar attachment in the present work. The attachment was unable to prevent canine tipping. This may have been due to the fact that the orthodontic force and moment delivered by the attachment may not meet his designed tooth movement.[13]

In an aligner system, the tooth tip often appears in the space close. To prevent side effects related to tooth tipping, in addition to using a highly elasticity aligner material and proper attachment design, order the aligner to upright by every four or five steps in space close stage may be another solution.

In conclusion, the purpose of the present study was to determine aligner behavior using an *in vitro* simulation. The attachments shape or size effects on tooth bodily movement were insignificant. The real behavior of orthodontic aligners during the course of treatment may require further research.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

Acknowledgments

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