ORIGINAL ARTICLE AJO-DO

The effects of aligner overtreatment on torque control and intrusion of incisors for anterior retraction with clear aligners: A finite-element study

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Introduction: The objective of this study was to analyze the effects of aligner overtreatment on torque control and intrusion of incisors for anterior retraction with clear aligners. **Methods:** Models including a maxillary dentition without first premolars, maxilla, periodontal ligaments, attachments, and aligners were constructed and imported to finite-element software. Two groups of models were created: (1) without canine attachment and (2) with canine attachment. Overtreatment degrees (0°, 1°, 2°, 3°, 4°, and 5°) were applied for both groups. **Results:** Clear aligner therapy caused lingual tipping and extrusion of incisors, distal tipping and extrusion of canines, and mesial tipping and intrusion of posterior teeth, which was more significant with canine attachments except for second premolars. Aligner overtreatment produced palatal root torquing and intrusion of incisors, distal tipping of canines, and mesial tipping of second premolars, with more significant in the condition with canine attachments. With canine attachments, 1.2° overtreatment could cause bodily retraction of central incisors. Without overtreatment, stress was concentrated on apical and cervical area of both labial and lingual surfaces of periodontal ligaments. The stress value was higher with canine attachments. However, when overtreatment was added, the stress was distributed more evenly. **Conclusions:** Clear aligner therapy produced lingual tipping and extrusion of incisors during anterior retraction. Overtreatment can achieve incisor intrusion and palatal root torquing, and the effect could be augmented by adding attachments on canines, which required more anchorage from posterior teeth. Appropriate overtreatment with placing attachments on canines should be designed to ensure bodily retraction and the least root resorption. (Am J Orthod Dentofacial Orthop 2022;162:33-41)

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Clear aligner therapy (CAT) is gaining popularity among both orthodontists and patients for its advantage of esthetics, comfort, and better oral hygiene over conventional appliances.[1-3] With creativity and innovations built into clear aligners, CAT is able to achieve various types of tooth movements, for example, intrusion, molar distalization, root torque, and incisor retraction.[4-7] However, the predictability and treatment complexity of tooth movement by CAT varied among different types of tooth movements.[7,8]

In particular, bodily retraction of incisors, frequently encountered among extraction cases, is a complicated tooth movement that requires adequate intrusion and torque control of incisors.[9] Otherwise, lingual tipping, extrusion, and clockwise moment of incisors may occur, which is called roller-coaster effect.[10] A recent study revealed that only 42% of root torque and intrusion of incisors could be achieved by clear aligners,[11] justifying that additional root torque and intrusion of incisors (overtreatment) should be designed to increase predictability of tooth movement. However, the effects of aligner overtreatment on incisor torque and intrusion are largely unknown. Moreover, torque control and intrusion of incisors by clear aligners require adequate anchorage from canines.[12] The design of attachments on canines guarantees a better aligner wrapping around incisors and renders more adequate force to be delivered, which may enhance the overtreatment effect on incisors. However, this notion has yet to be validated.

Three-dimensional finite element analysis (FEA), an effective computer simulation technique, has been widely applied to calculate stress and deformation developed on a geometric solid submitted to external force.[13] It has been suggested as a solution for complex biomechanical analyses and has been widely applied in orthodontics.[14,15] In FEA studies, many different simulations could be examined, and the most appropriate one could be suggested for future clinical validation, avoiding unnecessary repetitive clinical trials.

Therefore, we conducted a finite-element study to examine the effects of aligner overtreatment on torque control and intrusion of incisors for extraction space closure with CAT and to compare the biomechanical systems of aligner overtreatment with and without vertical rectangular attachments on canines.

MATERIAL AND METHODS

One healthy adult orthodontic patient requiring the extraction of 4 first premolars was selected as the subject of this study. The study was approved by the ethical committee of West China Hospital of Stomatology, Sichuan University (WCHSIRB-OT-2020-160). Three-dimensional geometric surface models of maxilla and maxillary dentition were constructed with the data of maxilla and maxillary dentition from cone-beam computed tomography and intraoral scanning by Mimics Research (version 17.0; Materialise, Leuven, Belgium) software and Geomagic Studio 2014 (3D Systems, Rock Hill, SC). Periodontal ligament (PDL) was modeled on root shape with an average thickness of 0.27 mm evenly. The alveolar fossa of maxilla was obtained after subtracting teeth and PDL from maxilla by Boolean operation. Then, first premolars and their PDL were removed to obtain extraction dentition and PDL models, and the dentition was named as D1. Horizontal rectangular attachments (3 × 2 × 1 mm) were designed on the buccal surfaces of posterior teeth. The aligner was developed by making an external offset, with the thickness of 0.5 mm according to the result of repeated measurements,[13] based on the simulated dentition and its attachments where the anterior teeth were retracted by 0.25 mm (named as D2). All the aforementioned components (maxillary dentition D1, maxilla, PDL, attachments, and aligner) were assembled and converted into a 3-dimensional FEA solid model with unstructured 4-noded tetrahedral elements in Hypermesh 14.0 (Altair, Troy, Mich). Defined after a convergence test, mesh size was set at 0.20 mm for dentition, 0.15 mm for PDL, 0.25 mm for maxilla, 0.20 mm for attachments, and 0.20 mm for aligners. The number of nodes and elements for all the components are summarized in Table I.

The models were assembled and imported into Abaqus/CAE (2016; SIMULIA, Providence, RI). The finite-element models of all components were displayed in Figure 1. Teeth, maxilla, attachments, and aligners were set as linear elastic. Teeth and maxilla were considered as isotropic and homogeneous materials without discriminating internal tissues.[16] No materials filled in the extraction space. Because there was no effect on long-term orthodontic tooth movement with linear or nonlinear elastic property of PDL,[17] the model of PDL was regarded as a linear elastic material for the best accuracy-computational ratio. As shown in Table II, the material properties of the components were taken from previous studies.[13,18,19]

The upper part of the maxilla was set as the boundary region in which the elements were limited to move, so that the maxilla remained absolutely fixed when the force was loaded. Bonded contacts were set between the internal surface of PDL and teeth and between the external surface of PDL and alveolar bone. Surface-to-surface contact was used between the aligner surface and teeth and attachments surfaces with a Coulomb friction coefficient of $\mu = 0.2$.[18] The surfaces of teeth and aligner contacted closely, and the nodes were one-to-one matched between the 2 contact surfaces. With the above settings, the contact calculation convergence of the model was realized.

Two group sets were designed in this study. Horizontal rectangular attachments (3 × 2 × 1 mm) were designed on the buccal surfaces of second premolars, first molars, and second molars for all the models in this study. For the first group set, 6 groups with different

Table I. Number of nodes and elements of the components of the finite element model

	Without canine attachment		*With canine attachment*	
Component	*Elements*	*Nodes*	*Elements*	*Nodes*
Teeth	1485245	315650	1485245	315650
PDL	1544678	417080	1544678	417080
Bone	4364816	921615	4364816	921615
Attachment	18608	5227	25654	7095
Clear aligner	883404	215228	919231	227146

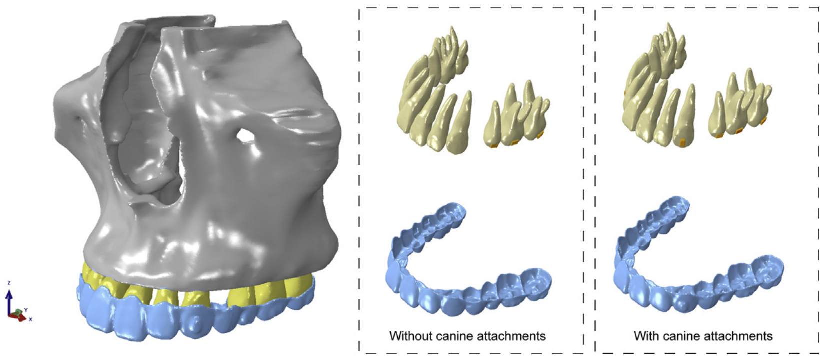

Fig 1. Computer-aided design model.

Table II. Material properties		
Component	*Young's modulus (MPa)*	*Poisson's ratio*
Teeth	1.96*10 ^ 4	0.30
PDL	0.67	0.45
Bone	1.37*10 ^ 4	0.30
Attachment	12.5*10 ^ 3	0.36
Clear aligner	528	0.36

degrees of aligner overtreatment (0°, 1°, 2°, 3°, 4°, and 5°) were designed. For the second group set, grouping details were similar with the first group set, except for that additional vertical rectangular attachments (2 × 3 × 1 mm) were designed on the labial surfaces of canines. Incisor retraction was simulated through decreasing the mesio-distal width of the first premolar aligner vacuoles by 0.25 mm, as mentioned before. Aligner overtreatment was achieved through anticlockwise rotation of anterior part of aligner around the center of the first premolar aligner vacuoles.

Global coordinate system was used to define the direction of x, y, and z axes. The direction of x-axis was the intersection of the coronal plane and the occlusal plane. The positive direction pointed to the left side of the patient. The direction of y-axis was sagittally perpendicular to the x-axis, with the positive direction pointing posteriorly. The direction of z-axis was vertically perpendicular to the x- and y-axes, with the positive direction pointing apically. Tooth displacement tendencies and equivalent stress of anterior teeth, PDL, and alveolar bone were analyzed. The incisal and apical center of anterior teeth and the occlusal center and apical center of buccal root of second premolars were taken as the measuring points.

RESULTS

As displayed in Figure 2, under the circumstance of no aligner overtreatment, incisors exhibited retraction, lingual tipping, and extrusion; canines were distally tipped and extruded; and second premolars were mesially tipped and intruded. These displacement tendencies were more significant with canine attachments than without canine attachments.

As depicted in Figure 3, without canine attachments, aligner overtreatment resulted in a palatal-torquing moment and intrusion effect on central incisors, while showing no effect on lateral incisors. Moreover, without canine attachments, the aligner overtreatment produced an additional distal tipping and extrusion effect on canines and a less mesial tipping and intrusion effect on premolars. In contrast, with canine attachments, the aligner overtreatment produced a palatal-torquing moment and intrusion on both central and lateral incisors. The additional distal tipping and extrusion effect on canines was more significant with canine attachments. Unlike the condition without canine attachments, second premolars received an additional mesial tipping and intrusion effect in the condition with canine attachments. Moreover, as depicted in Figure 4, aligner overtreatment could produce more labial tipping of central and lateral incisors, more distal tipping of canines, and more mesial tipping of second premolars with canine attachments than without canine attachments.

As shown in Figure 5, bodily retraction of central incisors was achieved when aligner overtreatment was 2.2° without canine attachments and 1.2° with canine attachments. Moreover, aligner overtreatment was unable to produce a bodily retraction of lateral incisors without canine attachments, but an overtreatment of 2.7° on lateral incisors was able to achieve a bodily movement of lateral incisors with canine attachments.

For central incisors, lateral incisors, and canines, with no aligner overtreatment, clear aligners mainly produced concentrated stress on cervical and apical area of labial surfaces and nonapical area of the whole palatal surfaces

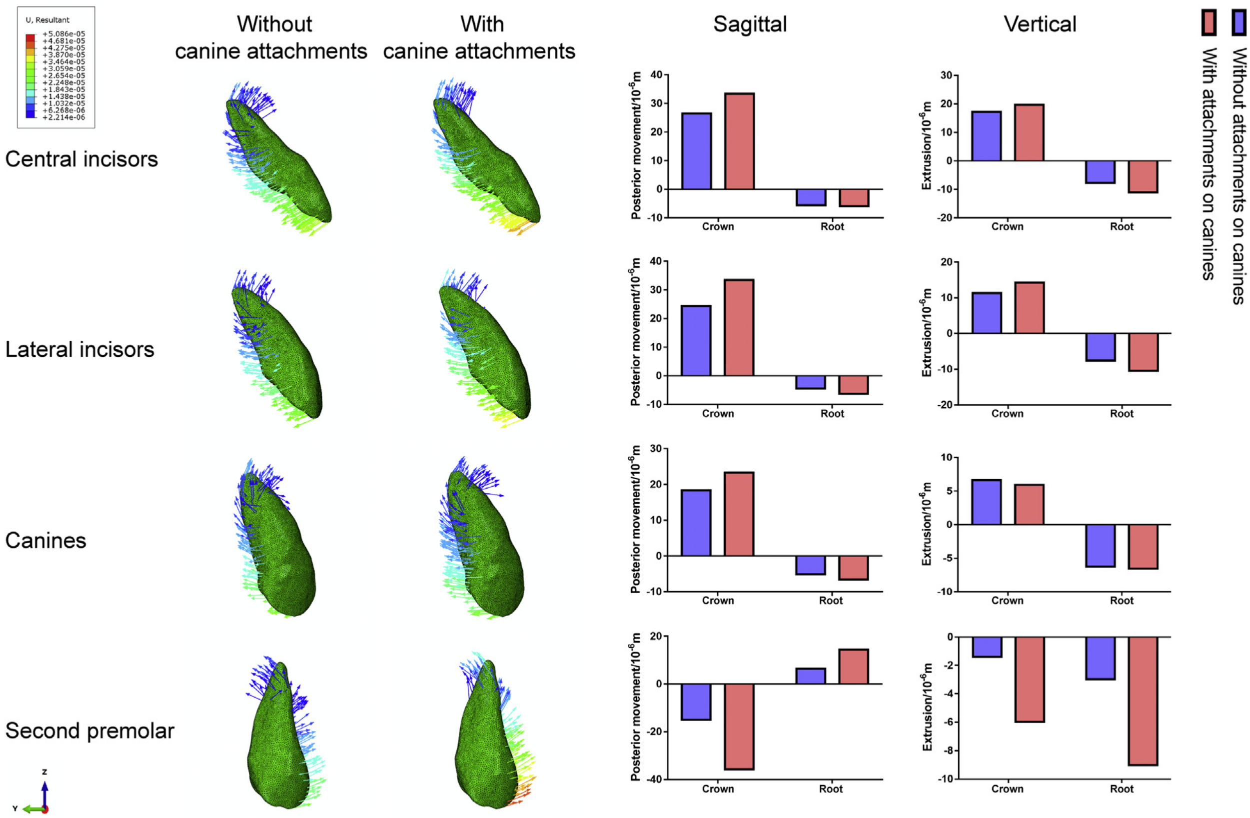

Fig 2. Displacement tendencies of central incisor, lateral incisor, canine, and second premolar when overtreatment was not added with and without canine attachments (unit: m).

(Fig 6). The concentrated stress was higher with canine attachments than without canine attachments. In contrast, the stress of PDL was distributed more evenly when aligner overtreatment was added.

For the second premolars, the stress was concentrated on both the mesial and distal root surfaces. The concentrated stress was higher with canine attachments than without canine attachments. However, aligner overtreatment resulted in a more evenly distributed stress for that without canine attachments but not for that with canine attachments.

DISCUSSION

Clear aligner offers several advantages over fixed appliances, for example, esthetics and comfort, but its treatment efficacy has been concerning because of varying predictability of tooth movement, especially for extraction cases.[7,20] A recent clinical study revealed that lingual tipping and extrusion of incisors and mesial tipping of posterior teeth occurred among extraction cases receiving clear aligners.[11] This is consistent with our present study, where we found that clear aligners produced retraction, lingual tipping and extrusion of incisors, distal tipping and extrusion of canines, and mesial tipping and intrusion of second premolars. From the perspectives of biomechanics, clear aligners exerted the retraction force (on anterior teeth) and protraction force (on posterior teeth) that were applied on crowns and passed through the occlusal side of the center of resistances, resulting in lingual tipping and extrusion of incisors, distal tipping of canines, and mesial tipping of posterior teeth. This phenomenon, called roller-coaster effect, is manifested as bite deepening, anterior interference, and posterior open bite, which is also encountered in conventional fixed appliances.[10] However, in contrast to fixed appliances, the inadequate stiffness of aligner materials makes it hard to sustain the tipping tendency,[21] rendering the roller-coaster effect more disastrous for clear aligners. For patients with chin retrusion, the lingual tipping and extrusion of incisors resulted in anterior interference and mandibular clockwise rotation, making chin retrusion more severe and jeopardizing facial esthetics. Moreover, we found that

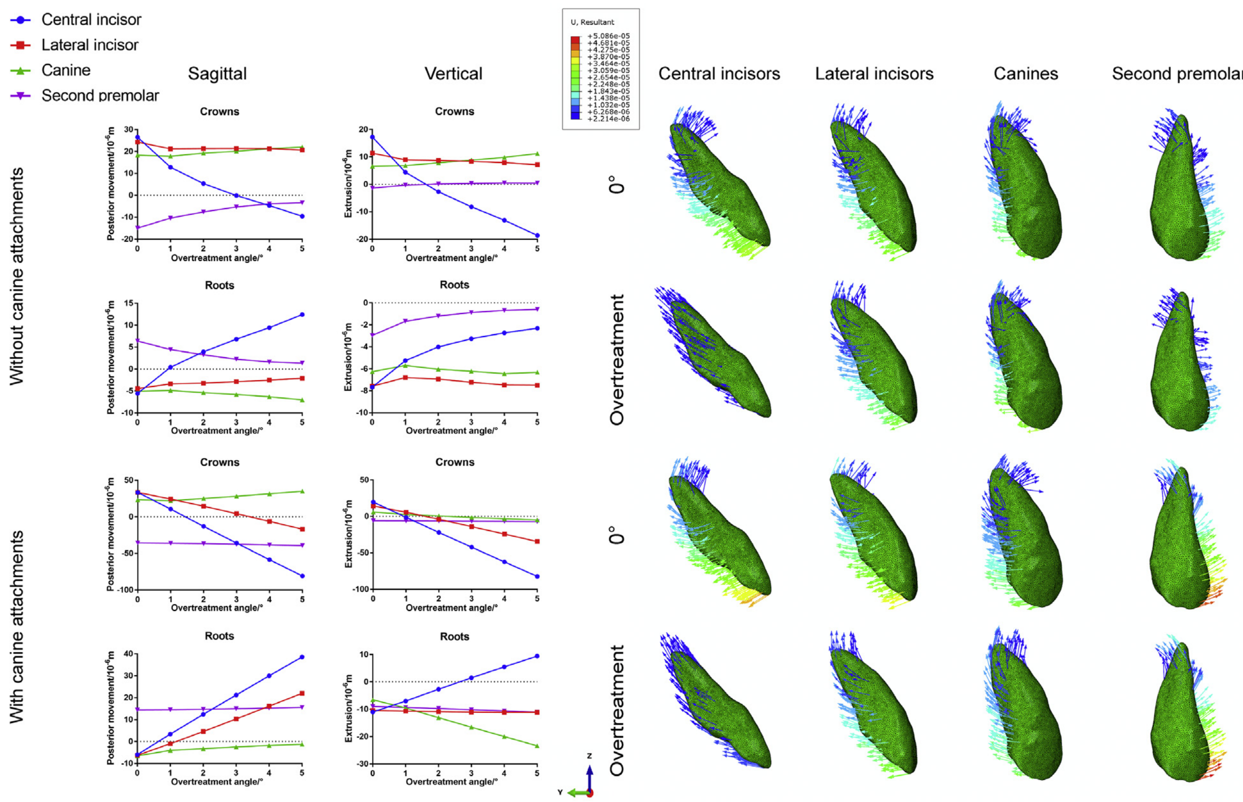

Fig 3. Change of displacement tendencies of central incisor, lateral incisor, canine, and second premolar when overtreatment was added and increased with and without canine attachments. The figure of displacement tendency of teeth was chosen at the overtreatment degree when bodily movement was achieved for central incisors (unit: m).

this roller-coaster effect, especially for the teeth adjacent to the extraction site, was aggravated in the condition with canine attachments as compared with that without canine attachments. In contrast to the absence of canine attachments, canine attachments ensured more adequate retention of clear aligner on dentition and prevented aligner from escaping from dentition. Thus, given that clear aligners achieve tooth movement through applying elastic force by fully wrapping around the designated crown areas,[22] the addition of canine attachments enhanced the designated tooth movement.

When the roller-coaster effect is encountered during clear aligner treatment, additional clear aligners (refinement) are often prescribed that aim to palatally torque and intrude incisors before the closure of extraction space.[11,23] Moreover, it has been revealed that 42% of incisor intrusion and palatal torquing could be achieved by clear aligners for extraction cases.[11] Thus, an overtreatment that offers additional palatal torquing and intrusion of incisors is well justified. Our results revealed that, without canine attachments, aligner overtreatment provided adequate palatal torquing and intrusion for the bodily movement of central incisors. As stated by Newton's third law of motion, for every action there is an equal and opposite reaction. The additional palatal torquing and intrusion of central incisors produced by the aligner overtreatment exerted a counterforce on clear aligners that subsequently generated a tendency of distal tipping and extrusion on canines, making canines more distal tipping and extruded. Interestingly, without canine attachments, we found that the aligner overtreatment was ineffective on lateral incisors, which could be attributed to off-tracking effect of clear aligners. Specifically, because the shape of clear aligners did not match the anterior teeth well when aligner overtreatment was added, clear aligners tended to escape from incisors and canines, rendering inadequate force delivered on anterior teeth. Moreover, given that force application by clear aligners is dependent on aligner-tooth contact, adequate aligner-tooth contact surface

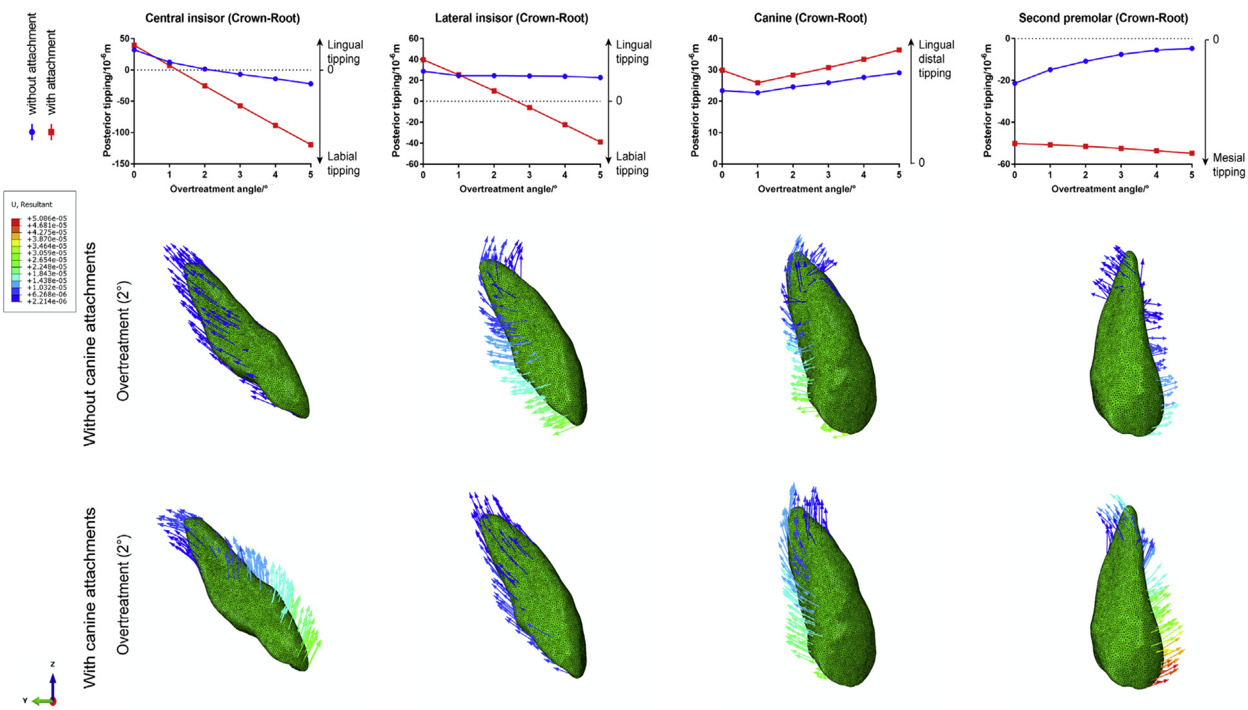

Fig 4. Comparison of tipping of central incisor, lateral incisor, canine, and second premolar between overtreatment with and without canine attachments (unit: m).

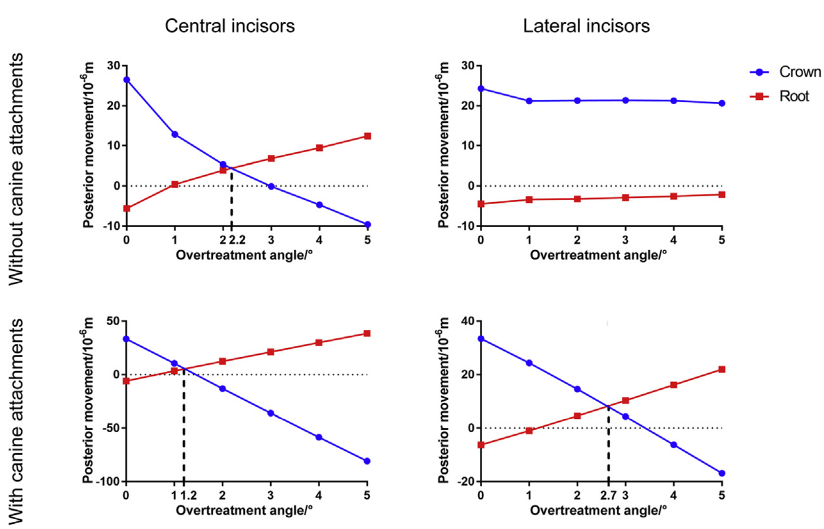

Fig 5. The overtreatment degree when bodily movement was achieved for central incisors and lateral incisors (unit: m).

is required for adequate force application. Thus, owing to the smaller crown surface of lateral incisors, the effect of aligner overtreatment was less effective on lateral incisors as compared with that on central incisors. This renders lateral incisors to be more susceptible to the off-tracking effect of clear aligners when aligner overtreatment was added. This off-tracking effect due to aligner overtreatment could explain the phenomenon that second premolars were less mesially tipped and less intruded with than without aligner overtreatment.

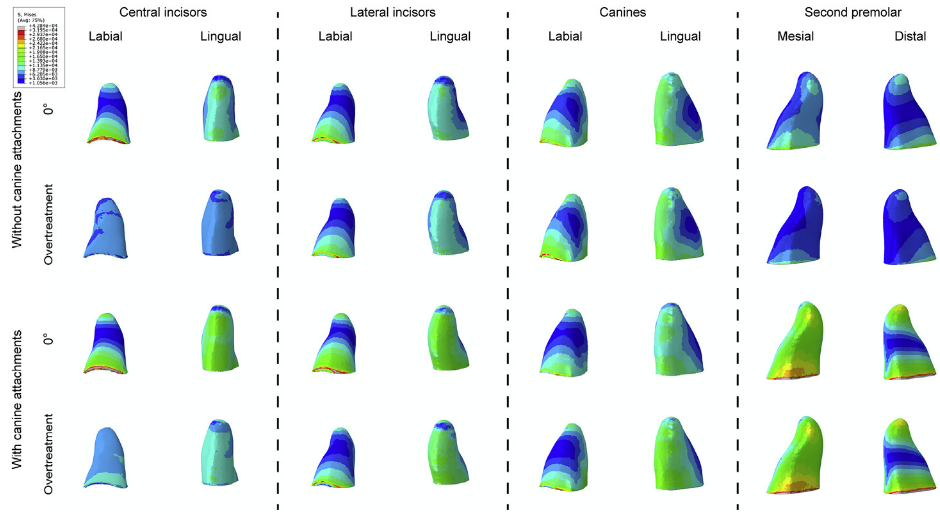

Fig 6. Equivalent stress of PDL of central incisor, lateral incisor, canine, and second premolar (unit: Pa).

Specifically, aligner overtreatment caused clear aligners to escape from teeth and delivered less force on second premolars; thus, mesial tipping and intrusion of second premolar were less prominent as compared with those with no aligner overtreatment in the condition without canine attachments.

Our results revealed that aligner overtreatment was able to offer adequate palatal torquing and intrusion for the bodily movement of both central and lateral incisors. As mentioned above, because canines were the anchorage teeth for incisor overtreatment, aligner overtreatment resulted in more distal tipping and extrusion of canines. The design of canine attachments ensured the adequacy of aligner wrapping around the dentition and rendered adequate force to be delivered. This resulted in a higher predictability of tooth movement, that is, more palatal torquing and intrusion of incisors (teeth to be moved) and more distal tipping and extrusion of canines (anchorage teeth). Moreover, our results revealed that aligner overtreatment produced a tendency of mesial movement with minimal tipping on second premolars. With canine attachments, no or minimal off-tracking effect occurred. The crowns of central incisors were displaced anteriorly by the aligner overtreatment, and the crowns of posterior teeth were mesially displaced, given that the length of clear aligners was fixed in the sagittal view, resulting in posterior anchorage loss. This is in accordance with the notion that bodily retraction of anterior teeth required more posterior anchorage. Anchorage loss is disastrous for maximal anchorage cases. Thus, anchorage preparation or absolute anchorage (temporary skeletal anchorage devices) may be considered for these patients. The horizontal rectangular attachments on second premolars were able to partially counter the tipping tendency of second premolars; thus, minimal tipping of second premolars was produced by the aligner overtreatment.

Aligner overtreatment is suggested for extraction cases receiving clear aligners. It has been claimed the aligner overtreatment was designed in Invisalign G6 and that Invisalign G6 was able to manage first premolar extraction cases very well. However, its clinical effectiveness was questioned by a clinical study where roller-coaster effect occurred in most of the patients,[11] which may be due to the inadequacy of aligner overtreatment. A recent study revealed that aligner overtreatment was effective in achieving bodily retraction of incisors.[12] However, the degrees of aligner overtreatment are still largely unknown. Our results revealed that, with canine attachments, the optimal degree of overtreatment was 1.2° for central incisors and 2.7° for lateral incisors. Because the retraction protocol was 0.25 mm in our model, we suggest that for every millimeter of incisor retraction, an overtreatment of 4.8° ($1.2°/0.25 \text{ mm} \times 1 \text{ mm} = 4.8°$) be designed to ensure bodily retraction roughly.

Root resorption is frequently encountered in clinical practice, and it has been reported that 91% of teeth underwent some degrees of root resorption after orthodontic treatment.[24] Although the incidence of root resorption was lower among patients receiving clear aligner as compared with those receiving fixed appliances, root resorption could not be avoided.[25,26] Maxillary central incisors were most susceptible to root resorption. Thus, we mainly discussed on central incisors. The force stress that is concentrated on root surfaces is the culprit for root resorption.[27] Our results revealed that the stress was concentrated on apical and cervical area of the labial root surfaces and on the non-apical area of the whole palatal root surfaces. This could be explained by the lingual tipping movement of central incisors: apical third of labial root surfaces moved anteriorly, and incisal third of palatal root surfaces moved posteriorly. Interestingly, we found that with aligner overtreatment, the stress was well distributed on PDL and no concentrated stress was detected for central incisors. This could be explained that appropriate aligner overtreatment resulted in a bodily retraction of incisors, and the retraction force was applied on the whole palatal root surfaces. This finding suggests that root resorption of incisors could be diminished by appropriate aligner overtreatment. Besides, alveolar bone defects, manifesting as bone fenestration and dehiscence, are not infrequently encountered in clinical practice, especially for labial alveolar bone. Labial alveolar bone defects are mainly due to inappropriate torquing control of incisors. As a result, apical third of incisor root moves anteriorly and may penetrate the labial alveolar bone, resulting in labial alveolar bone defects. After aligner overtreatment was designed, the stress was well distributed, suggesting that appropriate aligner overtreatment could decrease the likelihood of alveolar bone defects.

FEA represents one of the best ways to analyze force systems delivered by orthodontic appliances. However, root length, root morphology, aligner material property, and the design of aligner trim line may have significant effects on the results and should be considered in future studies. In the clinical scenario, an air gap between an aligner and a dentition is filled with saliva. Although the air gap was not designed in this model, this issue was well addressed by setting up appropriate friction coefficient between the aligner and the dentition. Yet, future studies taking this air-gap issue into consideration are called for. Moreover, the exact degree of aligner overtreatment should be validated in clinical settings. However, for clinicians and researchers, this degree of overtreatment (4.8°/mm) could offer a recommended value for aligner overtreatment and prevent relevant researchers from choosing empirical values or testing incremental values from 0 to 10 (or even greater).

CONCLUSIONS

1. CAT for extraction patients caused lingual tipping and extrusion of incisors, distal tipping and extrusion of canines, and mesial tipping and intrusion of posterior teeth, resulting in a roller-coaster effect. Adding vertical rectangular attachments on canines enhanced the aforementioned tooth movements.
2. Overtreatment in clear aligners was effective in controlling palatal root torquing and intrusion of incisors, resulting in bodily retraction of incisors.
3. The root torque control and intrusion for lateral incisors are less effective than those of central incisors.
4. Overtreatment effect could be augmented by adding attachments on canines, which required more anchorage from posterior teeth.
5. Appropriate aligner overtreatment (eg, 4.8°/mm in this model) with canine attachments should be designed to ensure bodily retraction and the least root resorption and alveolar bone defects.

AUTHOR CREDIT STATEMENT

Lu Liu: methodology, software, formal analysis, visualization, writing - original draft; Qinxuan Song: methodology, software, data curation; Jing Zhou: formal analysis; Qianyun Kuang: formal analysis; Xinyu Yan: formal analysis; Xiaoqi Zhang: formal analysis; Yue Shan: formal analysis; Xiaolong Li: resources; Hu Long: conceptualization, writing - review and editing, supervision; Wenli Lai: conceptualization, writing - review and editing, funding acquisition.

SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ajodo.2021.02.020.

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