Finite Element Analysis of Stress in Maxillary Dentition during En-masse Retraction with Implant Anchorage

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Abstract

The goal of this study was to investigate how the height of the archwire hook and implant anchor affect tooth movement, stress in the teeth and alveolar bone, and the center of resistance during retraction of the entire maxillary dentition using a multi-bracket system. Computed tomography was used to scan a dried adult human skull with normal occlusion. Three-dimensional models of the maxillary bone, teeth, brackets, archwire, hook, and implant anchor were created and used for finite element analysis. The heights of the hook and the implant anchor were set at 0, 5, or 10 mm from the archwire. Orthodontic force of 4.9 N was systematically applied between the hook and the implant anchor and differential stress distributions and tooth movements observed for each traction condition. With horizontal traction, the archwire showed deformation in the superior direction anterior to the hook and in the inferior direction posterior to the hook. Differences in traction height and direction resulted in different degrees of deformation, with biphasic movement clearly evident both in front of and behind the hook. With horizontal traction of the hook at a height of 0 mm, all the teeth moved distally, but not with any other type of traction. At a height of 5 mm or 10 mm, deformation showed an increase. The central incisor showed extrusion under all traction conditions, with the amount showing a reduction as the height of horizontal or posterosuperior traction increased. The center of resistance was located at the root of the 6 anterior teeth and entire maxillary dentition. The present results suggest that it is necessary to consider deformation of the wire and the center of resistance during en-masse retraction with implant anchorage.

Key words: Finite element analysis — En-masse retraction — Implant anchor — Center of resistance — Wire deformation

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Introduction

Recently, implant anchors have been used in orthodontics to provide secure anchorage, allowing many teeth to be moved simultaneously (en-masse retraction) over a short treatment term without the need for patient cooperation. Such anchors are generally either screw- or miniplate-type. Both types are used for movement of single or multiple teeth, or even the entire dentition. The miniplate-type is usually more suitable for achieving en-masse movement of multiple teeth or the entire dentition, however.

Orthodontic tooth movement used to be analyzed in relation to orthodontic forces acting on the center of resistance. There are many newer methods available now, however, which enable a more nuanced approach. These include theoretical analysis, laser holography, the strain gauge, the photoelasticity method, the displacement gauge, magnetic sensors, and electronic speckle pattern interferometry. The FEA approach is considered useful in the biomechanical analysis of tooth movement, as in vivo measurement of structural stress is difficult. Through recent advances in computer technology, a complicated 3-dimensional (3D) object can be effectively converted into an equivalent computerized model for simulation by means of FEA.

Many clinical studies and biomechanical analyses have investigated posterior movement of the anterior teeth using implant anchorage. Few clinical reports and biomechanical analyses regarding en-masse retraction of the entire maxillary or mandibular dentition are available, however. Nonetheless, understanding the biomechanical variables associated with implant anchors in orthodontics is very important, because the height and position of the hooks and implant anchors affect tooth movement.

The purpose of this study was to determine how the height of the archwire hook and implant anchor affect tooth movement, stress in the teeth and alveolar bone, and the center of resistance during retraction of the entire maxillary dentition using a multibracket system based on a 3D finite element model.

Materials and Methods

A dried adult human skull with normal occlusion was scanned using computed tomography (CT). The CT imaging conditions were as follows: tube voltage, 120 kV; tube current, 130 mA; scanning speed, 0.75 sec/rotation; bed movement velocity, 3 mm/sec; collimation, 4×1 mm; and gantry angle, 0°. Consecutive slice images were obtained at a reconstruction slice thickness of 1.25 mm and slice interval of 1.0 mm.

1. Preparation of finite element model

A 3D computerized model of maxillary bone and tooth was prepared based on CT data using the Mimics 11.0 3D image processing and editing software (Materialise N.V. Co., Belgium). The superior surface of the base of the maxilla was set to be parallel with the occlusal plane, 10 mm above the apex of the root of the canine, without replicating the nasal aperture or maxillary antrum. The maxillary model comprised cortical bone with a thickness of 1.5 mm and cancellous bone. Teeth and periodontal membrane with a thickness of 0.2 mm were also modeled.

Finally, the brackets, archwire hook, and implant anchors were constructed using the software. A standard rod-shaped, miniplate-type implant anchor was simulated. This shape was chosen for its analytical simplicity. In the maxillary dentition, each tooth was isolated from its adjacent tooth to allow observation of free wire deflection and tooth movement.

The models were then analyzed using the FEA program ANSYS 11.0 (Cybernet Systems for Swanson Co., USA). The models simulated the left half of the maxilla and teeth from the central incisor to the second molar. A bracket was placed at the center of the crown of each tooth, i.e., the LA point of Andrews LF, following which the archwire...
was set to pass through the slot in each bracket. The dimension of the archwire was assumed to be $0.019 \times 0.025$ inches. A perpendicular hook was placed on the archwire between the canine and first premolar. A miniplate-type implant anchor was placed between the second premolar and first molar; the base portion of the implant was fixed to the maxillary base; and the hook portion of the implant was isolated from the archwire (Fig. 1).

2. Material and physical properties

This model included both the cortical and cancellous elements of maxillary bone, the teeth, the periodontal membrane, brackets, archwire hook, and implant anchor. Each component of the model was defined as a 3D tetrahedral solid element. The total number of nodes was 222,391, and the total number of elements was 136,459. Material constants for each component in the model were set according to the finite element method, as detailed in Table 1. The material properties were all assumed to be homogeneous and isotropic and have a linear elastic body.

3. Restraining and loading conditions

The base of the maxilla was set in full restraint. The bracket was connected to the archwire to prevent friction, as this makes it much easier to observe initial stress and determine the position of the center of resistance. The implant anchor and maxillary base were also connected as well as the hook and archwire to establish full restraint. Finally, the ANSYS system was used to replicate the symmetrical right-side counterpart, thereby enabling an analysis of the full maxillary environment.

With this computer model fully constructed, an orthodontic force of 4.9 N (500 gf) was applied between the implant anchor and the hook. The traction height of the hook was systematically placed at 3 different levels above the archwire: 0, 5, or 10 mm. The traction point was determined on the basis of clinical use of a miniplate-type implant anchor, and this was also positioned at 0, 5, and 10 mm above the archwire. In total, 5 configurations were constructed from the combinations of these heights and traction conditions (Fig. 2).

4. Analysis

The principal maximum and minimum stresses in the teeth and maxilla were determined to investigate the dynamic state of the initial load in each direction. Positional changes were recorded at the middle point of the crown incisor edge and occlusal surface (Fig. 2). To help with this analysis, a coordinate system was defined in relation to the X-axis (medio-lateral direction), Y-axis (antero-posterior direction), and Z-axis (superior-inferior direction). Moreover, the amount of 3D displacement of a point 5 mm from the archwire on the hook was also mea-
sured to analyze the degree of deformation of the archwire.

Results

1. Horizontal traction

1) Hook10–Anchor10 (Fig. 2-a)

(1) Principal stress distribution (Fig. 3-a)

With maximum principal stress, tensile stress was observed on the labial surface of the anterior teeth, and on the mesial surface of the molars. Strong tensile stress was noted on the cuspal side of the canine bracket, and on the cervical side of the first premolar bracket. In addition, tensile stress in alveolar bone was observed in the anterior palate. With minimum principal stress, compressive stress was observed on the cervical labial surface of all the teeth, and on the lingual surface of the anterior teeth, as well as the distal surface of the molars. Strong compressive stress was noted on the cervical side of the canine bracket, and on the cuspal side of the first premolar bracket. Compressive stress of the alveolar bone extended around the canine as far as the area of the first molar.

(2) Three-dimensional displacement of teeth (Table 2)

On the Y-axis, the canines moved $3.35 \times 10^{-3}$ mm anteriorly, whereas the other teeth moved posteriorly. The first premolar moved most posteriorly ($-4.98 \times 10^{-3}$ mm), which decreased the amount of displacement toward the posterior teeth. On the Z-axis, the lateral incisors and canines moved $0.48 \times 10^{-3}$ mm and $5.98 \times 10^{-3}$ mm superiorly, respectively. The other teeth also moved inferiorly, and this was most pronounced in the first premolar ($-5.09 \times 10^{-3}$ mm), although again this decreased the amount of displacement toward the posterior teeth. Anteroinferior and posterosuperior inclination, i.e., counterclockwise rotation of the occlusal plane, was independently noted in the anterior and posterior segments. On the X-axis, the first and second premolars moved medially, whereas the other teeth moved laterally. This was most noticeable in the canines ($-6.08 \times 10^{-3}$ mm). There was a flattening of the anterior segment, and a reduction in the anterior area of the molar segment on the arch form.

### Table 2 Displacement of tooth crown with horizontal traction

| Direction       | X-axis (Medial+, Lateral-) | Y-axis (Anterior+, Posterior-) | Z-axis (Superior+, Inferior-) |
|-----------------|---------------------------|-------------------------------|-------------------------------|
| Hook10–Anchor10 | -0.13                     | -0.73                         | -0.32                         |
| Hook5–Anchor5   | -1.34                     | -0.36                         | 0.48                          |
| Hook0–Anchor0   | -6.08                     | 3.35                          | 5.98                          |
| Canine          | -0.14                     | -0.13                         | -0.07                         |
| Lateral incisor | -1.34                     | 2.25                          | 0.93                          |
| Central incisor | -0.13                     | 2.25                          | 0.93                          |
| First premolar  | 4.54                      | -4.98                         | -5.09                         |
| First molar     | -0.14                     | -0.55                         | -0.75                         |
| Second premolar | 0.93                      | -1.55                         | -0.75                         |
| Second molar    | -0.15                     | -0.55                         | -0.75                         |

X-axis (medio-lateral), Y-axis (antero-posterior), and Z-axis (superior-inferior)
(3) Three-dimensional change in hook (Table 3)

The 5-mm point on the hook moved $-74.62 \times 10^{-3}$ mm posteriorly on the Y-axis, $6.29 \times 10^{-3}$ mm superiorly on the Z-axis, and $-11.61 \times 10^{-3}$ mm laterally on the X-axis.

2) Hook5–Anchor5 (Fig. 2-b)

(1) Principal stress distribution (Fig. 3-b)

With maximum principal stress, tensile stress was observed on the labial surface of the anterior teeth, and on the mesial surface of the molars. Strong tensile stress was noted on the cuspal side of the canine bracket, and on the cervical side of the first premolar. Tensile stress in alveolar bone was also observed on the anterior palate. Although stress distribution here was similar to that under H10–A10 conditions, the range of distribution showed a reduction. With minimum principal stress, compressive stress was observed on the cervical labial surface of all the teeth, and on the lingual surface of the anterior teeth and distal surface of the molars. Strong compressive stress was noted on the cervical side of the canine bracket, and on the cuspal side of the first premolar bracket. Compressive stress in alveolar bone extended around the canine as far as the area of the first molar. Although the entire stress pattern was similar that under H10–A10 conditions, the range showed a reduction.

(2) Three-dimensional displacement of teeth (Table 2)

On the Y-axis, the canines moved $1.30 \times 10^{-3}$ mm anteriorly, while the other teeth moved posteriorly. Except for in the central and lateral incisors, the range of posterior movement showed a decrease in comparison with under H10–A10 conditions. The first premolar moved the most posteriorly ($-3.05 \times 10^{-3}$ mm), but this movement decreased the amount of displacement toward the posterior teeth. On the Z-axis, the canine and second molar moved $2.86 \times 10^{-3}$ mm and $0.003 \times 10^{-3}$ mm superiorly, respectively. In contrast, the other teeth moved inferiorly, and this was most pronounced for the first premolar ($-2.67 \times 10^{-3}$ mm), although this movement decreased the amount of displacement toward the posterior teeth. Similar to under H10–A10 conditions, the anteroinferior and posterosuperior inclination, i.e., the counterclockwise rotation of the occlusal plane, was independently noted in the anterior and molar segments. On the X-axis, the first and second premolars moved medially, whereas the other teeth moved laterally. Flattening of the anterior segment and a reduction in the anterior part of the molar segment on the archform, similar to under H10–A10 conditions, was also observed, but the range showed a reduction.

(3) Three-dimensional change in hook (Table 3)

The 5-mm point of the hook moved posteriorly, superiorly, and laterally, similar to under H10–A10 conditions. The amount of movement showed a decrease, however.
3) Hook0–Anchor0 (Fig. 2-c)

(1) Principal stress distribution (Fig. 3-c)

With maximum principal stress, tensile stress was observed on the labial surface of the anterior teeth, and on the mesial surface of the molars. In this case, strong tensile stress was noted on both the cuspal side of the canine bracket, and on the cervical side of the first premolar bracket. Tensile stress in alveolar bone was also observed on the alveolar crest. With minimum principal stress, compressive stress was observed on the cervical labial surface of all the teeth, and on the distal surface of the molars. Strong compressive stress was noted on the cervical side of the canine bracket. Compressive stress in alveolar bone was observed on the palate of the anterior teeth.

(2) Three-dimensional displacement of teeth (Table 2)

On the Y-axis, all the teeth moved posteriorly. The anterior teeth moved the most, but this movement progressively decreased the amount of displacement toward the posterior teeth. On the Z-axis, the second molar moved $0.008 \times 10^{-3}$ mm superiorly, whereas the other teeth moved inferiorly. The central incisor moved the most inferiorly ($-0.58 \times 10^{-3}$ mm), which decreased the amount of displacement toward the posterior molar, positioning it superior to the second molar. The counter-clockwise rotation of the occlusal plane was comparatively flat compared with under H10–A10 and H5–A5 conditions. On the X-axis, all the teeth moved laterally, i.e., lateral expansion of the arch form was observed.

(3) Three-dimensional change in hook (Table 3)

The 5-mm point of the hook moved posteriorly on the Y-axis, inferiorly on the Z-axis, and laterally on the X-axis.

2. Posterodistal traction

1) Hook0–Anchor10 (Fig. 2-d)

(1) Principal stress distribution (Fig. 4-d)

With maximum principal stress, tensile stress was observed on the labial surface of the anterior teeth, and on the mesial surface of the molars. Strong tensile stress was noted on the cuspal side of the canine bracket, and on the cervical side of the first premolar bracket. Tensile stress in alveolar bone was observed on the alveolar crest, from the canine to the premolar, and on the palate of the anterior teeth. With minimum principal stress, compressive stress was observed on the cervical labial surface of all the teeth, and on the distal surface of the molars. Strong compressive stress was noted on the cervical side of the canine bracket. Compressive stress in alveolar bone was observed on the palate of the anterior teeth.

(2) Three-dimensional displacement of teeth (Table 4)

On the Y-axis, all the teeth moved posteriorly. The central and lateral incisors moved the most, at $-0.71 \times 10^{-3}$ mm and $-0.89 \times 10^{-3}$ mm, respectively, whereas the degree of posterior molar movement showed a decrease. On the Z-axis, the canine moved $1.07 \times 10^{-3}$ mm and second molar $0.006 \times 10^{-3}$ mm superiorly, whereas the other teeth moved inferiorly. Compared with horizontal traction, the amount of inferior movement of the central incisor ($-0.44 \times 10^{-3}$ mm) was similar.

The counter-clockwise rotation of occlusal plane was comparatively flat compared with under H10–A10 or H5–A5 conditions. On the X-axis, all the teeth moved laterally, i.e., lateral expansion of the arch form was observed.

(3) Three-dimensional change in hook (Table 3)

The 5-mm point of the hook moved posteriorly on the Y-axis, superiorly on the Z-axis, and laterally on the X-axis.

2) Hook0–Anchor5 (Fig. 2-e)

(1) Principal stress distribution (Fig. 4-e)

With maximum principal stress, tensile stress was observed on the labial surface of the anterior teeth, and on the mesial surface of the molars. Strong tensile stress was noted on the cuspal side of the canine bracket, and on the cervical side of the first premolar bracket. Tensile stress in alveolar bone was observed on the alveolar crest, from the canine to the
premolar. With minimum principal stress, compressive stress was observed on the cervical labial surface of all the teeth, and on the distal surface of the molars. Strong compressive stress was noted on the cervical side of the canine bracket. Compressive stress in alveolar bone was observed on the palate of the anterior teeth as far as the premolar and distally from the molars.

On the Y-axis, all the teeth moved posteriorly. The degree of posterior movement showed a progressive decrease. On the Z-axis, the canine moved $0.49 \times 10^{-3}$ mm and second molar $0.007 \times 10^{-3}$ mm superiorly, whereas all the other teeth moved inferiorly. Compared with under H0–A10 conditions, all the teeth showed a large amount of movement. The counter-clockwise rotation of occlusal plane was comparatively flat compared with under H10–A10 or H5–A5 conditions, however. On the X-axis, only the central incisor moved medially, while all the other teeth moved laterally, i.e., lateral expansion of the arch form was observed.

(3) Three-dimensional change in hook (Table 3)
The 5-mm point of the hook moved posteriorly on the Y-axis, superiorly on the Z-axis, and laterally on the X-axis.

Discussion

1. Study methods
This investigation employed methods that have previously been utilized in other studies. Sung et al. successfully used the finite element analysis to find the center of resistance, after setting the coefficient of friction between the wire and the bracket at zero without restricting axial freedom. Furthermore, Togo et al. investigated anterior tooth movement by restraining the teeth with wires and analyzing the initial stress in a friction-free model. Meanwhile, other comparative studies have considered the impact of friction. Tominaga et al. set the coefficient of friction at 0.2, whereas Jeong et al. immobilized the dentition with an archwire on the buccolingual side and a splint wire on the lingual side to investigate tooth alignment under nearly rigid conditions. These various efforts determined that friction exerts little effect on initial stress, allowing the present study to investigate the pattern of tooth movement in response to initial stress and the center of resistance.

In this study, the model was defined as a...
rigid body in which no abrasion occurred between the bracket and archwire to facilitate determination of tooth dynamics based on initial stress results. The degree of freedom of the wire was not restricted in any direction, however, and linear analyses were performed in accordance with the method of Togo et al.\textsuperscript{33}, which permits the teeth to move in 3 dimensions. As the loading condition, 4.9 N of traction force was applied. This value was decided on with reference to the clinical report of Sugawara \textit{et al.}, who retracted the entire maxillary dentition using implant anchors\textsuperscript{28}.

2. Results of horizontal traction

When horizontal traction was employed, the central incisor extruded and moved lingually under all conditions. Compared to the central incisor, the lateral incisor and canine showed differential movement. Under H10–A10 conditions, the lateral incisor intruded, and the canine both intruded and moved mesially. Likewise, under H5–A5 conditions, the canine intruded and moved mesially. Under H0–A0 conditions, however, the canine extruded and moved distally. These results suggest that deformation of the archwire depends on the amount of movement of the hook (Table 3). Traction height appears to play a major role here. Traction from a high position, such as Hook10, generated a rotational movement that caused the hook to slant distally and laterally, resulting in deformation of the archwire, which may in turn have decreased tension on the canine, allowing it to slant laterally and exert compressive stress on the first and second premolars (Fig. 5-a). Vertical and lateral hook movements rarely occurred under H0–A0 conditions, however, resulting in little archwire deformity. When posterosuperior traction was employed under H0–A10 and H0–A5 conditions, both distal and lateral movement of the hook was observed, although this was much smaller than that under H10–A10 or H5–A5 conditions, and there was little deformation of the archwire. Therefore, when traction arose from a low position of the hook, deformation of the archwire was suppressed. In addition, in the occlusal view, such deformation was more pronounced with an increase in traction height. Regarding stress distribution, tensile stress in the cervicopalatal area of the canine suggests buccal movement, whereas compressive stress on the cervicopalatal area of the first and second premolar suggests lingual movement. This movement possibly caused deformation of the wire. Moreover, because the hook’s outer surface was used as a traction point, the mesial surface rotated toward the buccal side, and distal surface toward the lingual side (Fig. 5-b). This indicates that 3D deformation of the archwire also affects the morphology of the dental arch.

Concerning archwire deformation, Kim \textit{et al.} reported that during retraction of the 6 anterior maxillary teeth, if the hook of the front tooth was placed high, the front tooth inclined more labially; and that the canines and premolars would extrude due to an increase in deformation of the wire\textsuperscript{12}. Tomioka \textit{et al.} determined that the center of resistance of an incisor was at a height of 7.5 mm during retraction of the 6 anterior maxillary teeth\textsuperscript{34}. The load caused bodily movement at a height of 5.5 mm to the mesial canine power arm and 11.2 mm to the distal canine power arm. They suggested that this was due to deformation of the archwire. In the present study, intrusion and labial inclination of the tooth in front of the hook and extrusion of the tooth behind the hook were observed when using a high-level traction hook.

In the lateral view, under H10–A10 conditions, the central and lateral incisors were extruded and retruded, but the canine intruded. Meanwhile, the first premolar was extruded and retruded, and second molar remained at an almost zero level position, thereby resulting in deformation of the archwire. This causes biphasic movement that differs in front of and behind the hook between the anterior teeth and molars (Fig. 6). In the anterior region, the anterior teeth were both extruded and retruded, even though intrusion force was applied due to archwire deformation. This may have been because an orth-
odontic force vector passes under the center of resistance.

A number of positions have been reported regarding the center of resistance in the anterior teeth. For the 4 upper anterior teeth, anteroposterior positions have been reported between the lateral incisor and canine, and also between the canine and first premolar\(^5,35,36\). In addition, vertical positions have been reported near the center of the tooth root toward the root apical side from the alveolar crest between the central incisors\(^35\). For the 6 upper anterior teeth, anteroposterior positions have been reported in the distal canine, or between the canine and first premolar\(^5,6,17,21,23,36\). Vanden Bulcke et al. reported that the center of resistance and vertical position of the central incisor were located in the apical region, 7 mm from the alveolar crest\(^35\). Lee et al. reported the position to be 6.76 mm apical to the cementoenamel junction\(^16\).

About the center of resistance in anterior teeth, in the present study, both extrusion and retrusion of the central incisor were observed, even at a traction height of Hook10. This suggests that the center of resistance of the anterior teeth is located above Hook10, i.e., 5 mm above the alveolar crest of the central incisor (Fig. 7).

In the molar region, deformation of the archwire causes the first premolar to extrude and the neighboring molars to be subjected to extrusion force, although the entire molar region moves in the posterosuperior direction.

Otsuka reported that the center of resistance in the maxillary molar teeth was located in the buccolingual direction near the mid-point between the mesiobuccal cusp and the palatal cusp of the first molar\(^20\). This was even though it was located within 1/3 of the tooth root length in the apical region in the axial direction. In addition, Kojima et al. reported that it was located near a height of 8 mm apically from the archwire on the distobuccal root of the first molar\(^15\).

About the center of resistance in the molars, in the present study, compressive stress in alveolar bone under horizontal traction gradually weakened as the height of the hook increased (H0<H5<H10), this is assuming that the center of resistance was located close to a height of 10 mm above the archwire in the molars. Our analyses revealed extrusion of the first premolar due to deformation of the archwire, indicating that we were unable to identify the center of resistance in the molars.

### 3. Results of posterosuperior traction

No large differences were observed in stress distribution between under H0–A10 and H0–A5 conditions. This may have been because the traction position was low under both conditions, and there was little overall rotational movement, causing the hook to slant distally. Excessive concentration of stress was observed, however, on the canine and first premolar, near the hook. Anterior tooth extrusion under H0–A10 conditions was less than that under H0–A5 conditions, but similar to that under H5–A5 conditions. This may have been due to application of posterosuperior traction, resulting in an upward traction vector toward the anterior teeth that was stronger than the parallel traction vector. In addition, extrusion of the molars was also less than that under H0–A5 conditions. This might similarly be explained by upward traction resulting from an upward traction vector near to the center of resistance in the molar region. Moreover, the distribution range of compressive stress in molar alveolar bone was less than that in the parallel traction group.

Archwire deformation was minor under both H0–A10 and H0–A5 conditions, although the occlusal plane from the central incisor to the second molar was flat. Moreover, under H0–A5 conditions, the amount of extrusion in the anterior teeth was slightly greater than that under H0–A10 conditions. In addition, under H0–A5 conditions, the amount of extrusion in the molars was also slightly greater. As described earlier, these findings might be explained by the fact that the upward vector angle was larger under H0–A10 conditions, and therefore may have passed closer to the center of resistance.
Teuscher reported that the center of resistance in the maxillary dentition was located centrally, between the first and second premolar roots\(^3\), while Billiet \textit{et al.} reported that it was at the lower edge of the malar prominence of the maxilla, similar to the center of resistance in the nasomaxillary complex\(^2\). On the other hand, Sung \textit{et al.}\(^30\) and Jeong \textit{et al.}\(^9\) both reported that the center of resistance in the full maxillary dentition was located on the second premolar root 11 mm superior and 26.5 mm posterior to the incisal edge of the maxillary central incisor. In addition, Kojima \textit{et al.} reported that the center of resistance in the full maxillary dentition was located in the second premolar root, with initial tooth movement 6.5 mm superior and 26.4 mm posterior to the maxillary central incisor, under conditions of simulated orthodontic tooth movement 7.0 mm superior and 25.8 mm posterior to the maxillary central incisor\(^14\).

About the center of resistance in the entire maxillary dentition, in the present study the entire dentition showed counter-clockwise rotation under H0–A10 conditions. This indicates that the center of resistance in the maxillary dentition is superior to under H0–A10 conditions. That is, by drawing a geometrical figure, the estimated position was located above the alveolar crest in the first premolar and about 4 mm above the alveolar crest in the second premolar (Fig. 8). In comparison, orthodontic force vector under H0–A5 conditions passed further below and away from the center of resistance, which may have caused the more pronounced counter-clockwise rotation observed.

4. Clinical implications

1. With retraction of the entire maxillary dentition, it is necessary to consider the centers of resistance in the anterior and molar teeth, as well as in the entire maxillary dentition, and deformation of the archwire.

2. The wire may be deformed by the hook; therefore, when using a hook, it is necessary to employ a highly rigid wire to prevent this outcome, and to bend the archwire to correct deformation.

3. It was shown that it is effective to raise the hook or to pull it upward and backward to reduce extrusion of the central incisor when moving teeth posteriorly.

4. In the straight wire method, a horizontal traction with a low hook height produces greater anterior teeth extrusion; therefore, it is necessary to bend a reverse curve in the archwire to prevent extrusion of the anterior teeth.

5. In deep bite cases requiring anterior teeth intrusion, the use of a high hook is advantageous.

6. In open bite cases requiring anterior teeth extrusion, the use of a low hook is advantageous.

Conclusions

This study used the computerized finite element method to analyze initial stress generated in the maxillary dentition during en-masse retraction of the entire maxillary dentition using an implant anchor. The following conclusions were drawn:

1. With traction of the hook at a height of 0 mm, all the teeth moved distally.

2. With traction of the hook at a height of 0 mm, extrusion of the central incisor decreased with increase in the height of the implant.

3. With horizontal traction of the hook at heights of 0, 5, or 10 mm, the higher the hook, the greater the deformation of the wire. This demonstrated biphasic movement, with the occlusal plane in front of the hook and the occlusal plane behind the hook rotating counter-clockwise.

4. With horizontal traction of the hook at heights of 0, 5, or 10 mm, the higher the hook, the smaller the amount of lingual and extrusion movement of the central incisor.

5. With horizontal traction of the hook at heights of 0, 5, or 10 mm, the higher the hook, the more distal movement and extrusion increased in the teeth behind it.

6. The center of resistance in the 6 anterior maxillary teeth was found to be 5 mm above the alveolar crest of the central incisor,
Fig. 1  Three-dimensional finite model
Model comprising maxillary bone, teeth, periodontal membrane, cortical bone, and cancellous bone, together with brackets, archwire, hook, and implant anchor. X, Y, and Z axes of rectangular nodal coordinate system and model size (mm) are shown.

Fig. 2  Traction from archwire hook to implant anchor
Hook and implant anchor traction points were each positioned at 3 different heights from archwire: 0, 5, or 10 mm. A total of 5 conditions resulted from these hook-height and traction-point combinations. Arrows indicate direction of traction. Hook and anchor values indicate height of loading point in mm. Yellow point of crown was point used to measure crown movement.

Fig. 3  Principal stress distribution for a (Hook10–Anchor10), b (Hook5–Anchor5), and c (Hook0–Anchor0)
Upper and lower rows show maximum and minimum principal stresses, respectively (Unit, MPa).
Fig. 4 Principal stress distribution for d (Hook0–Anchor10) and e (Hook0–Anchor5)
Upper and lower rows show maximum and minimum principal stresses, respectively (Unit, MPa).

Fig. 5 Displacement of teeth and archwire
a) Lateral view  b) Occlusal view
These figures express 200 times actual amount of movement.

Fig. 6 Movement of dentition
Red arrow and line show movement of anterior teeth, and blue arrow and line show movement of posterior teeth. In lateral view, under H10–A10 conditions, central and lateral incisors showed extrusion and retraction; canine, intrusion; and first premolar, extrusion and retraction; all resulting in deformation of occlusal plane. This may have caused biphasic movement in front of and behind hook, between anterior teeth and molars.

Fig. 7 Center of resistance in anterior teeth
Red arrow shows direction of traction and blue arrow shows incisor tooth extrusion. Green area shows position based on center of resistance. Extrusion and retraction of central incisor observed, even under traction at height of Hook10. This suggests that center of resistance in anterior teeth is above height of Hook10, i.e., 5 mm above alveolar crest of central incisor.

Fig. 8 Center of resistance in entire maxillary dentition
Red arrow shows H0–A10 conditions and blue arrow shows H0–A5 conditions. Central incisor and second molar arrows show each intrusion and extrusion. Green area represents position based on center of resistance. Entire dentition showed counter-clockwise rotation under H0–A10 conditions, indicating that center of resistance in maxillary dentition was superior, i.e., estimated position was located above alveolar crest at first premolar and approximately 4 mm above alveolar crest at second premolar.
whereas in the entire maxillary dentition it was estimated to be located above the alveolar crest at the first premolar and approximately 4 mm above the alveolar crest at the second premolar.

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