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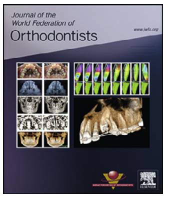

Research Article

Effect of sinus proximity, alveolar bone level, and initial buccolingual inclination on behavior of maxillary first molar under expansion force: a finite element analysis

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ABSTRACT

Background: The primary aim of this study is to determine whether sinus proximity increases or decreases molar tipping under the force of expansion; a secondary aim is to compare the effect of the initial buccal inclination, alveolar bone loss, and sinus proximity to molar movement under expansion force, by assessing the stress distribution of the periodontal ligament and the changes in the moment/force (M/F) ratio.
Methods: Twenty different 3-dimensional models were created by changing the buccal inclination (0°,5°,10°,15°, and 20°) value of maxillary molar and simulating different amounts of alveolar bone loss (0, 2,4, and 6 mm) in the basic model. Additionally, an artificial sinus was added to the basic model, and the penetration of the roots into the sinus to different levels (2, 4, and 6 mm) was simulated separately. Thus, 9 additional models were created. The M/F ratio, location of the center of resistance, and principal stresses on the periodontal ligament were analyzed for each of the 29 models separately in a finite element analysis.
Results: The M/F ratio increased as initial buccal inclination or bone loss increased. As the amount of simultaneous penetration of 3 roots into the sinus increased, the M/F ratio decreased. Incremental changes of both the initial inclination value and the amount of bone loss resulted in higher maximum compressive stress on the apices of the buccal roots.
Conclusions: Increases in alveolar bone loss and buccal inclination caused increases in the periodontal stress. Penetration of the roots into the sinus provides bicortical anchorage and could prevent unwanted crown tipping.

1. Introduction

When orthodontic force is loaded on a tooth, various levels of stress-strain distribution occur in the periodontal ligament (PDL) and surrounding alveolar bone. This allows the tooth to be displaced in the alveolar bone. The amount and type of displacement can be affected by various parameters, such as the size and shape of the tooth, the PDL thickness, adjacent anatomical structures, initial buccolingual inclination, and the alveolar bone level [1], because these factors cause changes in the moment/force (M/F) ratio. As a result, even if the direction and magnitude of forces are constant, the displacement behavior of tooth varies.

The maxillary first molar is subjected to severe orthodontic force in the transverse direction via the banded rapid maxilla expansion device or hybrid hyrax device [2,3]. Similarly, a certain amount of force is applied to the molar with devices such as the trans palatal arch or quad helix, even though the force is not as great as in rapid expansion [4,5]. Buccal crown tipping of the tooth occurs during the transverse movement of the maxillary molar, causing extrusion of the palatal cusps [6]. However, with the changes in the M/F ratio, a more controlled movement of the tooth can be achieved. In other words, extrusion of the palatal cusps can be minimized [7].

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Several studies have investigated the effect of different levels of alveolar bone loss on the stress distribution on the PDL and the pattern of tooth movement. But in these studies, the molar was simulated to be in the upright position [8,9], whereas the maxillary first molars are typically buccally inclined toward the occlusal plane. Buccal crown tipping may occur as a compensatory mechanism for maxillary transverse deficiency or as a result of alveolar bone loss, especially in adult patients [10,11]. Different initial inclination values may cause different patterns of movement under the same force. Therefore, a minimum moment is delivered for each unit of force, to achieve less buccal tipping during maxillary expansion in a patient with an increased initial inclination or horizontal bone loss. Both the alveolar bone loss and the degree of initial inclination affect the distribution of stress-strain in the PDL [7]. The magnitude and distribution of orthodontic force affect tissue reactions, resulting in bone formation, bone resorption, or external apical root resorption [12].

The maxillary sinus is an important anatomical structure that should be considered for dental applications (implants, extractions, or endodontic procedures) in the maxillary posterior teeth [13]. The maxillary sinus floor (MSF) may occasionally extend into the interradicular area, and the root tips of the molar teeth may penetrate into the sinus cavity [14,15]. We believe that the proximity between the MSF and the root apices may be a factor that affects the behavior of the maxillary first molar under orthodontic load. In previous studies, the relationship between bone loss and molar tooth movement was analyzed by assessing the stress–strain distribution or M/F ratio [16,17]. However, neither the variation in the initial inclination of the molar nor the proximity between the roots and the MSF have been investigated. We believe that this study is the first to evaluate the effect of the proximity of the maxillary sinus on maxillary molar movement. In addition, the stress–strain distribution, center of resistance (Cres), center of rotation, quantity of movement, and direction of the palatal cusp, root tips, and cervical region were assessed.

The primary aim of this study is to determine whether sinus proximity increases or decreases molar tooth tipping under the force of expansion. The effect of sinus proximity was interpreted in relation to the influence of alveolar bone level and initial buccolingual inclination.

2. Materials and methods

2.1. Basic solid model creation

Ethical approval for the study was provided by the Afyonkarahisar Health Science University Clinical Research Ethics Committee. Written consent for publication was obtained from each participant. The computed tomography image of the appropriate patient was selected from the archive and imported into Mimics 21.0 software (Materialise NV, Leuven, Belgium) in DICOM (digital imaging and communications in medicine) format. The maxillary first molar of the patient had no restorations, root canal treatment, or morphological malformation. By setting an appropriate threshold value for the skeletal tissue, a three-dimensional (3D) image of the patient's head was created (minimum of 226 Hounsfield units [HU], and maximum 3071 HU, as instructed in the Mimics software) [18]. Subsequently, the maxillary first molar was separated from the other structures. The 3D stereolithography (STL) model of the tooth was converted to a 3D computer-aided design (CAD) model, using Ansys SpaceClaim software (Ansys, Canonsburg, PA). The tooth measured 22.5 mm in height (from the palatal root apex to the mesiopalatal cusp tip), and the crown's mesiodistal and buccopalatal widths were 11.3 and 13 mm, respectively. The palatal root length (vertical distance from the alveolar crest to the apex) was 12.8 mm, and the mesiobuccal and distobuccal root lengths were 11.7 mm [8]. In the same software, a 0.25-mm–thick PDL was first simulated around the roots. The alveolar bone was designed to be 1 mm above the cervical line. The long axis of the tooth was inclined 5° from the occlusal plane, in accordance with the normal value [19]. An orthodontic attachment was modeled by imitation of the palatal shield dimensions (height: 1.5 mm; width: 3.5 mm) of a molar band (3M, Maplewood, USA) and placed on the palatal crown surface of the tooth.

Table 1
Material properties levels

Material	Young's modulus (MPa)	Poisson's ratio
Periodontal ligament	0.05	0.49
Cortical bone	2000	0.30
Cancellous bone	200	0.30
Teeth	20,000	0.30
Bracket	200,000	0.30

2.2. Variations in basic models

The long axes of the modified molar models were inclined buccally at 0°, 5°, 10°,15°, and 20° relative to the axis of the normal molar model. Alveolar bone loss (0, 2, 4, and 6 mm) was assumed to be equal in all directions (buccolingual and mesiodistal), following the cement enamel curvature. Finally, a total of 20 models (5 inclinations and 4 levels of bone) were generated to evaluate the effect of bone loss and initial inclination (Fig. 1).

To evaluate the relationship between the root apex and the proximity of the sinus floor, an artificial sinus was added to the basic model, and the penetration of the roots into the sinus at various levels (2, 4, and 6 mm) was simulated separately (Fig. 2). Cortical bone thickness of the MSF was uniformly designed to be 0.5 mm [20]. However, the levels of penetration were altered by treating buccal roots as a single root in order to reduce the number of model variations and better interpret the results, in order to reduce the number of model variations and allow for clear interpretation of the findings. Consequently, 9 different models were produced for the purpose of assessing the effect of the proximity between root apices and the MSF.

2.3. Construction of finite element models

All 29 models were imported into Ansys Workbench, version 21.0 (Ansys) for the construction of finite element models. Mechanical properties of the PDL, tooth, cortical bone, cancelous bone, and bracket were identified per previous research (Table 1) [21]. All materials were assumed to be linear-elastic, isotropic, and homogeneous. Each of the structures in the models was transformed into a 3D tetrahedral mesh to form elements and nodes.

2.4. Loading, boundary conditions, and finite element analysis

A 100 N expansion force (F) was applied from the palatal crown surface perpendicular to the long axis of the tooth to simulate the buccal tipping movement of the maxillary molar [7,16]. Five points on the tooth surface (apices of the roots, cervical point, and mesiopalatal cusp tip) were determined. A counter-tip moment of force (Mt) that caused the crown to move toward the palate was used to detect the Cres. Each of the 29 models was subjected to a second force that resulted in bodily tooth movement in order to determine Cres localization. The distance between the second force

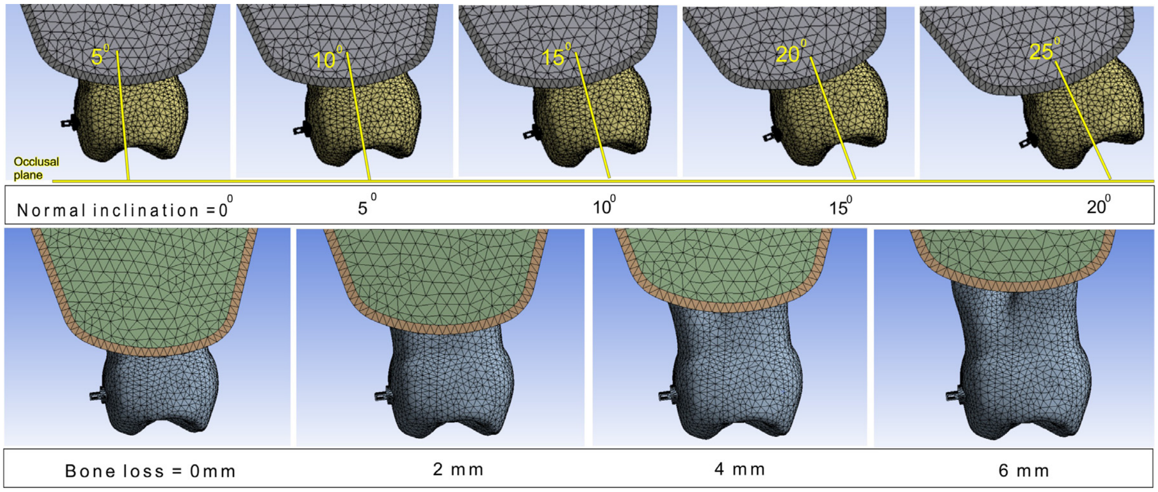

Fig. 1. A total of 20 maxillary molar models with 5 different buccal inclination values and 4 levels of bone loss were created.

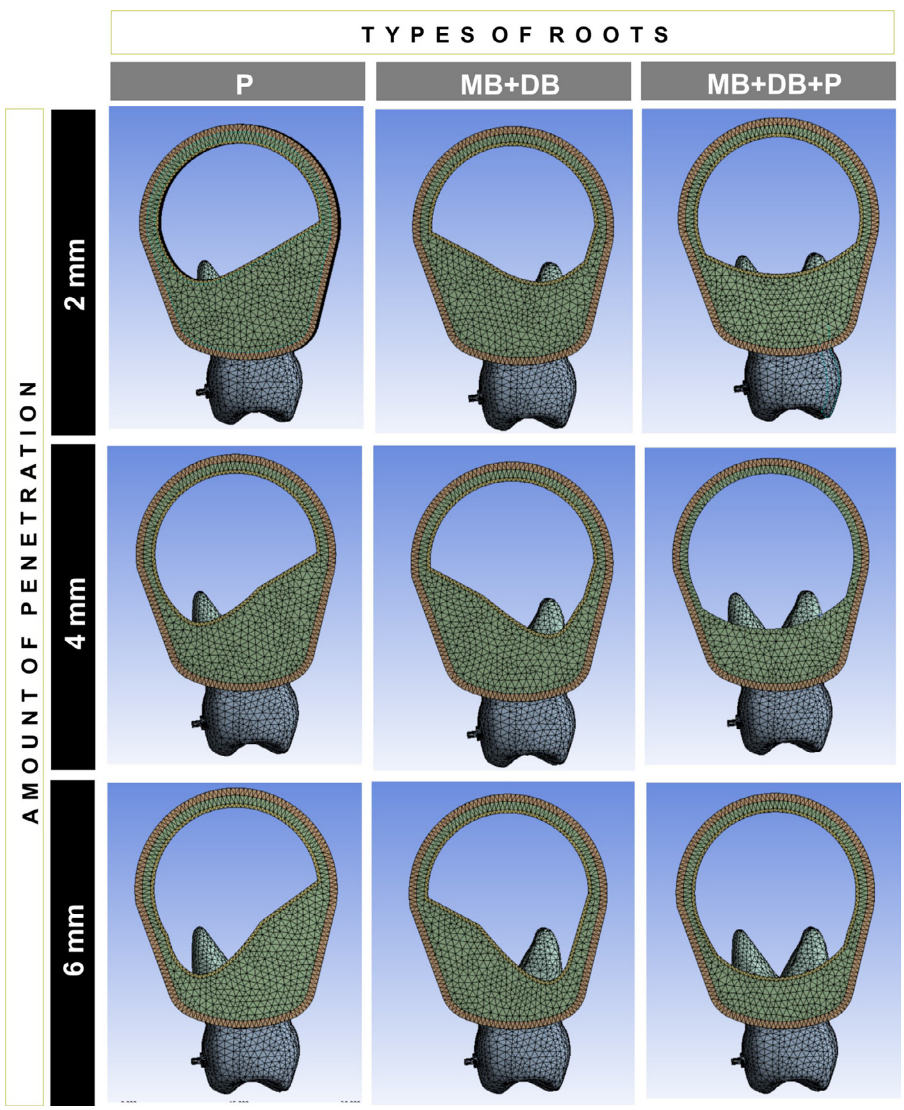

Fig. 2. A total of 9 additional models were obtained with root penetration at different levels (2, 4, and 6 mm). DB, distobuccal root; MB, mesiobuccal root; P, palatal root.

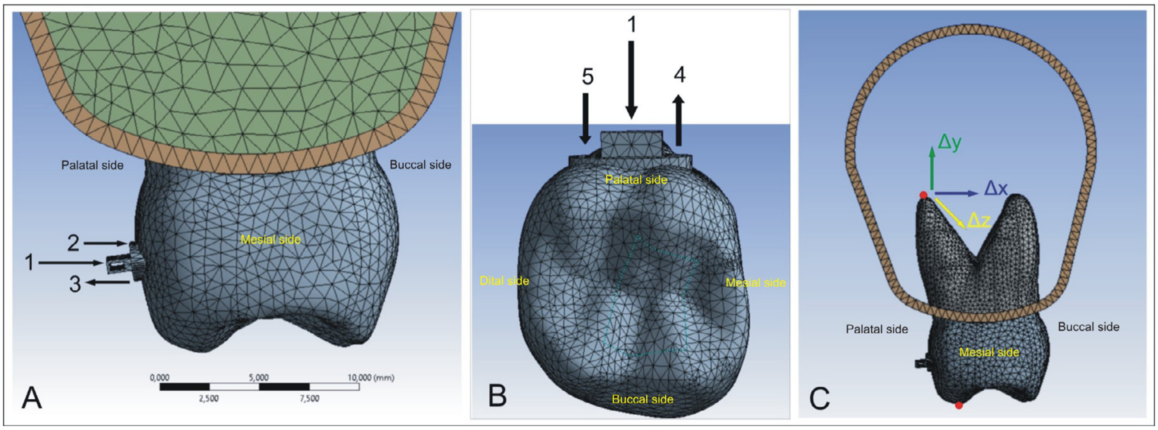

Fig. 3. Forces associated with the 3 diffirent loads applied to each of the 29 models. (A) The first force (100gf) was applied parallel to the occlusal plane at the midpoint of the bracket. The second load was a coupled force (2, 3) that generated a counter-tipping moment. (B) The third load was applied as a coupled force (4, 5) to create an anti-rotation moment. (C) A total of 3 red points placed at the apex of the palatal root, the tip of the mesiopalatal, and the distopalatal cusp were allowed to move only on the x-axis. The movement of the 3 red dots on the y- and z-axis was minimized.

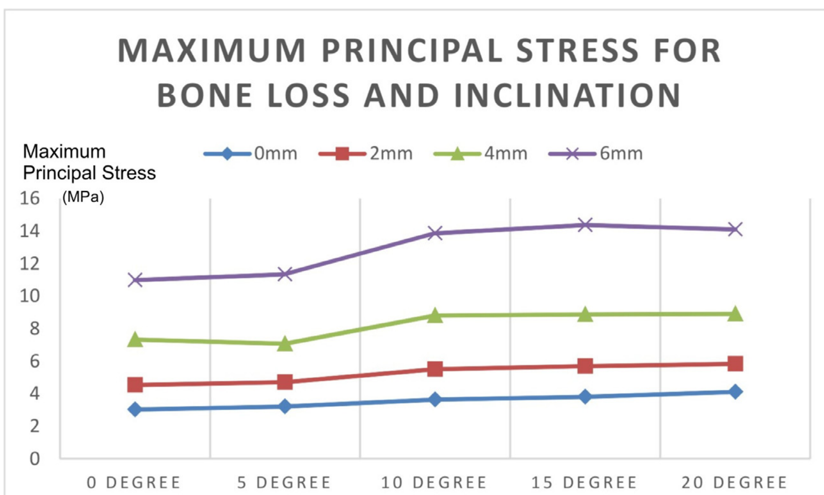

Fig. 4. Maximum compressive stress of the models with different amounts of alveolar bone loss and different buccal inclinations.

application point and the bracket was measured. The Mt was created by applying a coupled force and allowed us to have a translatory movement of a tooth (Fig. 3). The length of the moment arm was 2 mm. The Mt/F ratio varied from 0 to 10. Additionally, a counter-rotation moment was created by applying coupled force to minimize the rotational movement caused by the asymmetrical structure of the molar. The length of the moment arm was 4 mm for the counter-rotation moment.

2.5. Evaluation of stress distubution on the PDL

The stress distribution on the PDL was calculated automatically by the software, based on the principal stress. Maximum tensile stress, maximum compressive values, and the M/F ratio of each model were recorded for comparison. The intersection point of 2 lines (the long axis of the upper molar before movement, and the long axis after movement) was detected. Then the distance (M/F = distance) from the point to the bracket was measured. Furthermore, stress localization (on the cervical or root surface) was interpreted comparatively.

3. Results

3.1. Variations in the centers of resistance

The change in the location of the Cres was examined for each amount of buccal inclination and alveolar bone loss. The increased buccal inclination and alveolar bone loss resulted in higher positioning of the Cres (Table 2). The highest Cres value was found for the molar with 6 mm of bone loss combined with an inclination of 20°.

The penetration of the palatal root into the sinus at various levels alone did not change the Cres localization, possibly owing to the movement of the resistance center in the buccolingual direction rather than in the vertical direction. For the 2-mm root penetration, the locations of the Cres in all 3 groups were very close to one another (Table 3). For the 4-mm and 6-mm penetrations,

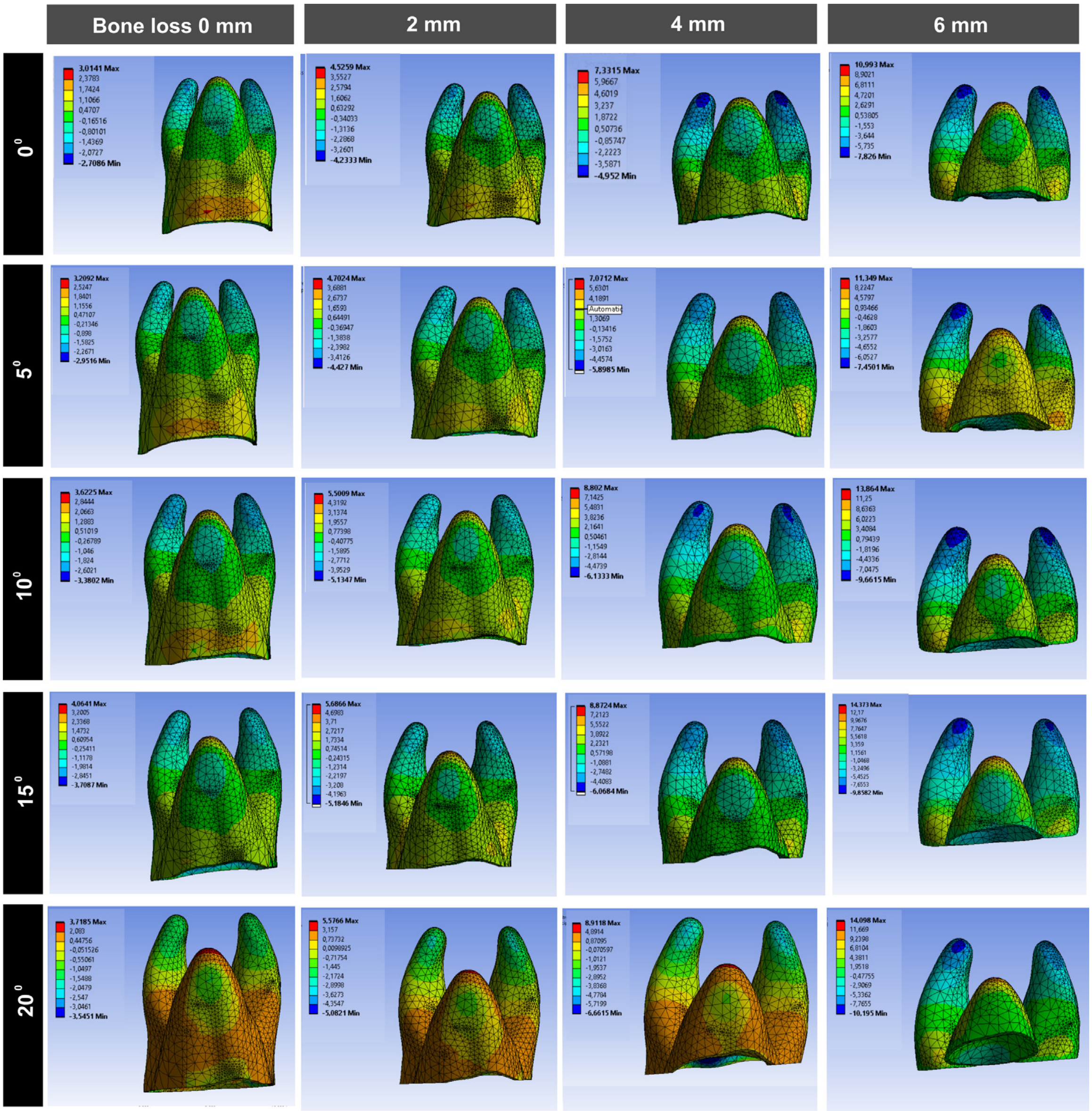

Fig. 5. The models with different amounts of alveolar bone loss and different buccal inclinations. Stress distribution patterns of the roots from the palatal view (red area: maximum tensile stress; blue area: maximum compressive stress).

as the number of penetrated roots increased, the Cres moved coronally.

3.2. Variations in the M/F ratio

The M/F ratio increased as initial buccal inclination or bone loss increased (Table 2). The highest M/F was found for the molar with 6 mm of bone loss combined with an inclination of 20°.

M/F ratios were found to be very close to each other in all 3 groups for 2-mm root penetration. As the amount of simultaneous penetration of the 3 roots into the sinus increased, the M/F ratio decreased (Table 3).

3.3. Maximum principal stress of the models

Incremental changes in both the initial inclination value and the amount of bone loss resulted in higher maximum compressive stress on the apices of the buccal roots (Figs. 4 and 5). The penetration of the roots into the sinus did not increase the amount of stress as much as the initial inclination or bone loss did, but it changed the location of the stress. Simultaneous penetration of all 3 roots into the sinus caused distribution of stress into the cervical region (Figs. 6 and 7). The maximum compressive stress on the buccal roots was increased by the singular penetration of the palatal root into the sinus. Similarly, penetration of the buccal roots has resulted in increased compressive stress on the palatal root.

4. Discussion

In previous studies using finite element models to evaluate the biomechanics of the tooth, the maxillary molar was simulated as being in an upright position [9]. Additionally, the proximity of the roots to the MSF has not been taken into account. This study inves-

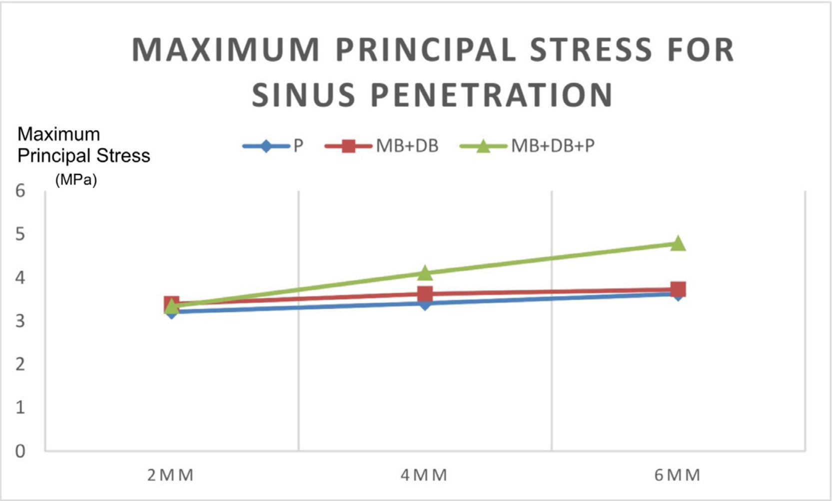

Fig. 6. Maximum compressive stress of the models with different amounts of root penetration. DB, distobuccal root; MB, mesiobuccal root; P, palatal root.

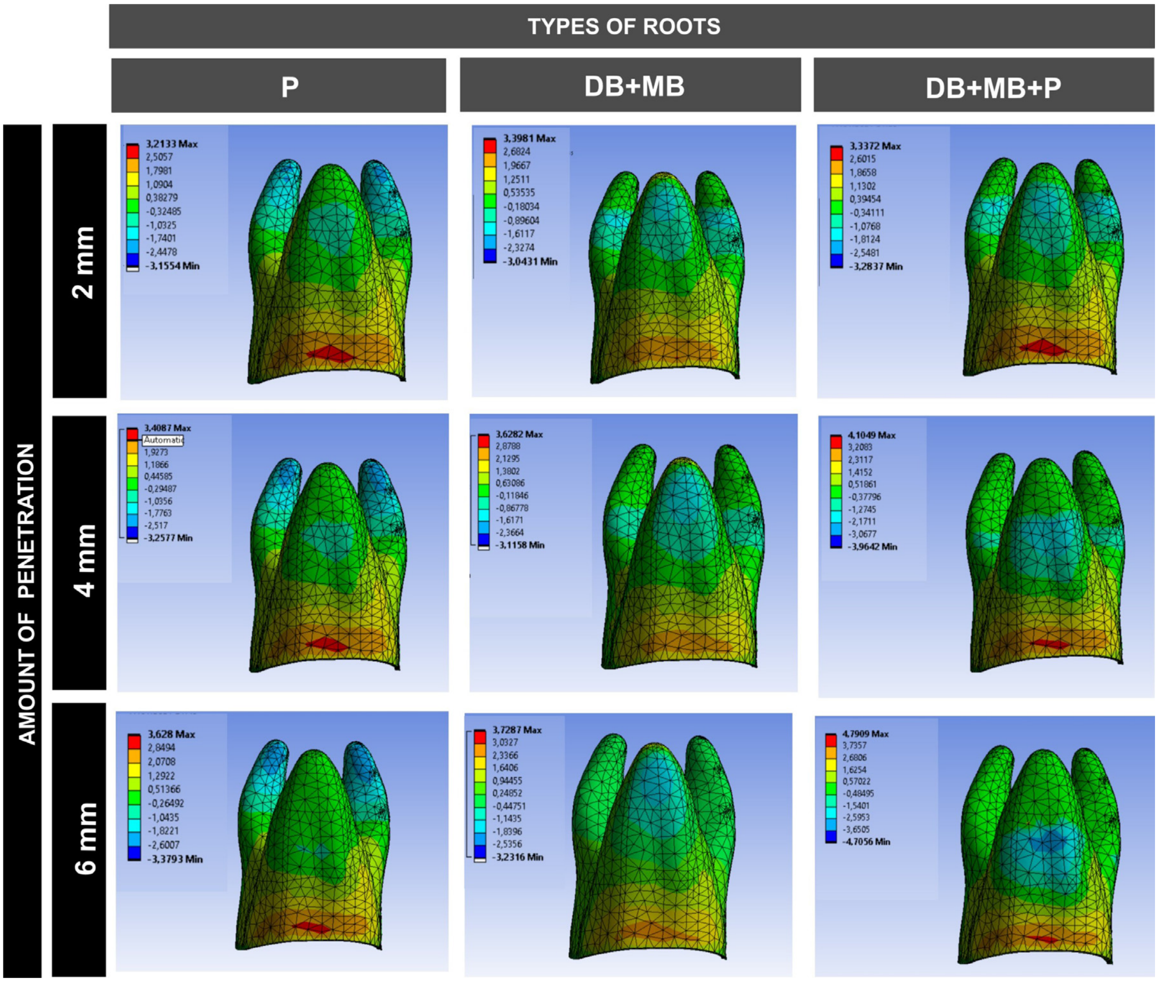

Fig. 7. The models with different amounts of root penetration and their stress distribution patterns from the palatal view. DB, distobuccal root; MB, mesiobuccal root; P, palatal root.

Table 2
Moment to force (M/F) ratios and the center of resistance location values occurring at different degrees of initial inclination and bone loss

M/F ratios

Initial inclination	Bone loss 0 mm	2 mm	4 mm	6 mm
0°	11.4	12.7	12.9	13.7
5°	12.1	12.9	13.2	14.3
10°	13.2	13.8	14.0	15.2
15°	14.0	14.6	14.9	15.9
20°	14.5	14.9	15.5	15.9

Center of resistance

0°	11.4	12.5	13.4	14.2
5°	12.1	13.0	13.9	14.8
10°	12.8	13.8	14.7	15.7
15°	13.7	14.2	15.0	15.8
20°	14.2	14.7	15.2	15.9

Table 3
As a result of the penetration of the roots into the sinus, changes in the moment to force (M/F) ratio and the center of resistance location. DB, distobuccal; MB, mesiobuccal; P, palatal.

M/F ratios

Types of roots	2 mm	4 mm	6 mm
P	11.07	10.87	10.7
MB + DB	11.33	11.72	12.1
P + MB + DB	10.98	10.5	9.8

Center of resistance

P	11.25	11.3	11.3
MB + DB	11.42	11.13	10.4
P + MB + DB	11.34	10.35	9.37

tigated how the tooth's initial inclination, alveolar bone loss, and maxillary sinus proximity affect tooth behavior and distribution of PDL stress. The maxillary first molar was selected for the study because it is typically used as an anchor tooth to correct the transverse maxillary deficiency. If the moment of the tooth is not correctly set, the buccal overtipping of the crown and the extrusion of the palatal cusp may cause open bite. The direction and magnitude of the load must be set correctly to avoid unwanted movement of the tooth and possible root resorption.

Sung et al. reported that the Cres moves toward the apex due to alveolar bone loss, but the relative distance between the Cres and the alveolar crest decreases [23]. Therefore, when the alveolar bone level or the PDL supports decreases, the magnitude of the force should be reduced and smaller moments should be created to achieve physiologically tolerable movement [23,24]. Due to the reduced bone support and PDL area, the same amount of force on the crown causes more PDL pressure than that occurs without bone loss. However, a decrease in bone support from the apical to coronal direction may be seen in maxillary molar teeth, owing to sinus proximity, similar to bone loss from the coronal to apical direction. This fact is sometimes overlooked by clinicians. We believe that the effect of sinus proximity on decrease in bone support for tooth movement has not been investigated previously.

In this study, it was observed that as alveolar bone loss increases, the initial tipping of the crown increases. This finding is consistent with the results of previous studies [22,24]. Cobo et al. reported that, due to alveolar bone loss, the Cres may be located above the alveolar bone crest [25]. Similar findings were obtained in our study. The Cres, on the other hand, moved more coronally as the penetration of the roots into the sinus increased. However, the change in the M/F ratio for the same models was not as pronounced as that in the Cres. The thickness of the cortical bone (0.5 mm) around the maxillary sinus may affect this change, because it provides bicortical anchorage by penetration of roots into the sinus. The bicortical retention affecting the biomechanics of tooth movement is considered to be similar to the bicortical anchorage provided by miniscrews [26,27].

Both alveolar bone loss and increased initial inclination caused an increase in maximum compressive stress at the root tips. This situation might trigger resorption of the roots. The singular penetration of the palatal root or the common penetration of 2 buccal roots increased the compressive stress on the root surface, and the stress was distributed on the root apices. We suggest that this distribution is related to the cortical bone around the maxillary sinus, which provides additional root resistance. The penetration of the palatal root into the sinus, to various levels, alone decreased the M/F ratio, an effect that may be related to the significant resistance shown by the buccal roots during the transverse movement of the tooth. The simultaneous penetration of all 3 roots into the sinus caused more cervical concentration of the maximum compressive stress, another factor that may increase or accelerate the risk of root resorption.

The buccal bone wall thickness of the maxillary molar varies [28,29]. The migration of the compressive stress toward the cervical region could reduce the bone thickness in patients with a thick bone biotype in the posterior region. If patients have a thin biotype, it may cause gingival recession. A thin biotype may also induce cervical resorption in cases with high bone density in the region where stress is concentrated [30].

This study has some limitations. Normally, PDL thickness is not uniform; it varies from apex to cervix [26]. Furthermore, PDL has nonlinear and anisotropic physiology due to tissue fluid in its structure [27]. However, in this study, the PDL was assumed to be uniform in thickness, linear, and isotropic. The shape (conical or rectangular) and length of the roots influence the position of the Cres and the distribution of stress in the PDL [31]. Yoshida et al. hypothesized that more-tapered roots result in a more occlusally located Cres [32]. In this study, real tooth morphology was simulated using the maxillary molar of a randomly selected patient. Important to keep in mind is the fact that the root forms, lengths, and distances are all factors that affect the results of the finite element analysis. The results obtained from a single tooth make it difficult to reach an overall conclusion. Due to wide anatomical variations in real life, the findings should be used as a reference for the clinical assessment of the biomechanics of tooth movement.

The main clinical implication of this study is that sinus proximity can reduce tipping by providing bicortical anchoring to the molar, particularly in devices that anchor directly to the molar, such as hybrid hyrax. Other implications are that more tipping can be expected in patients with a greater initial buccal–lingual inclination, and the expansion force may cause more molar tipping in adults with reduced alveolar bone levels or patients with periodontal disease. Further clinical studies are required to test all of these clinical implications, particularly the main finding regarding the effect of sinus proximity.

5. Conclusions

- Increasing both the amount of bone loss and the initial inclination value resulted in more apical movement of the center of resistance and increased maximum compressive stress.
- The penetration of the roots into the sinus did not increase the maximum compressive stress as much as did alveolar bone loss and change of the initial inclination. However, it caused stress distributions to be concentrated in a more cervical position.

- The simultaneous penetration of all 3 roots into the sinus created a bicortical anchorage effect and reduced the M/F ratio. This effect may allow clinicians to produce less crown tipping during maxillary expansion.

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