Original article

Finite element analysis of mandibular molar protraction mechanics using miniscrews

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Summary

Background/Objectives: The aim of this study was to determine the most desirable force system to achieve molar protraction from an interdental miniscrew minimizing side-effects. Several iterations of force delivery were simulated through variations in the height of a miniscrew, length of a molar extension arm, and incorporation of a lingual force.

Materials/Methods: A three-dimensional mesh model of the right posterior segment of the mandible was developed from cone beam computed tomography data from a patient missing a first molar. Protraction appliances were constructed using computer-aided design software and integrated with finite element software. After mesh generation, a total of 80 loading conditions were simulated by altering the extension arm length (2–10 mm), miniscrew height (0–8 mm), and magnitude of protraction force from the lingual side (0–1.5 N). A constant labial force of 1 N was used in all models.

Results: As the length of the extension arm increased, mesial tipping decreased, rotation decreased, and buccolingual inclination remained the same without lingual traction force. Lingual traction reduced rotation but increased tipping. Similar trends were observed in all situations despite of the height of the miniscrew.

Conclusions: The height of the miniscrew is not as critical in affecting tooth movement during mandibular second molar protraction as the length of the extension arm. The most ideal force system in the model appeared to be the longest extension arm (10 mm) with the addition of a lingual force of half or equal magnitude of the labial force.

Introduction

Mandibular molar protraction has been reported as a challenging procedure because of the molar’s large root surface area, density of mandibular bone, and significant anchorage demands. Temporary anchorage devices (TADs) have been introduced in the orthodontics as effective tools in providing absolute anchorage for molar protraction. Although TADs encompass miniscrews and miniplates, clinically interdental miniscrews have been preferred for molar protraction.

Freudenthaler et al. (1) published a preliminary study regarding the biomechanics of mandibular protraction using miniscrews. However, most of the evidence related to the mechanics of molar protraction has been from numerous case reports describing this...
procedure (2–5). Although miniscrews are used as effective adjuncts in orthodontics, there is a lack of evidence regarding the appropriate anatomical sites for their placement that would be biomechanically favourable in molar protraction. Furthermore, the types of loading conditions necessary for a translatory movement of the molar need to be analyzed.

Finite element (FE) method is a common tool used to evaluate different loading conditions in order to optimize the biomechanics delivered. Many FE studies related to orthodontic mechanics have been recently reported (6–10). Most of the recent studies on miniscrews using FE have concentrated on the stress distribution around the miniscrews in an effort to understand how loading conditions affect their stability (11–13). In fact, Holberg et al. (14) evaluated a model of molar protraction with direct and indirect anchorage concentrating in the osseous stress distributions around the miniscrews instead of the teeth. A recent study evaluated the most effective loading conditions for the en masse retraction of the anterior segment from miniscrews (15); however, no study has evaluated the most effective mechanics for mandibular molar protraction.

The location of the miniscrew, the point of force application, and the presence of a lingual force may affect the type of tooth movement achieved during mandibular molar protraction. A three-dimensional (3D) FE model could help simulate the best loading conditions to allow for the least side-effects in mandibular molar protraction into edentulous spaces. The aim of this study was to evaluate the loading conditions that result in most effective molar protraction with the least side-effects through a set of permutations achieved by altering the height of the miniscrew, length of an extension arm, and the presence of a lingual force.

Materials and methods

A mandibular second molar protraction model using miniscrews was created based on clinical reports describing the technique (3–5). In these reports, antero-posterior miniscrew location has been selected to be mesial of the second premolar.

Modelling of solid components

Cone beam computed tomography (CBCT) data from a 27-year-old male patient who presented with a missing mandibular right first molar was selected for modelling of anatomical components. The scan (CB MercuRay™, Hitachi Medical Corporation, Tokyo, Japan), with a voxel resolution of 0.25 mm, was taken at the University of Connecticut Health Center. The CBCT images were saved as digital imaging and communication in medicine format and loaded into image-based modelling software Simpleware™ (Version 6.0, Simpleware, Exeter, UK) to create solid models. The grey scale threshold was used to identify and distinguish the molar, premolar, and mandibular bone. These elements were segmented and constructed. To create the cortical and trabecular bone separately, the lumen of alveolar bone was filled with floodfill tool and duplicated. The dilation tool was used on this duplicated filled mandibular bone to shrink about 10 voxel (2 mm) from its surface and then cortical and trabecular bones were generated by Boolean operation. The periodontal ligament (PDL) was constructed by duplication and expansion of the root of the molar by 1 voxel (0.25 mm) away from the surface of the tooth. After the modelling was finished, all anatomical components were exported as a non-uniform rational b-splines (NURBS) surface model.

A protraction appliance based on a bracket, an extension arm, and a miniscrew was constructed using computer-aided design (CAD) software Autodesk Inventor™ (Version 2012, Autodesk Inc., Mill Valley, California, USA). The buccal tube was designed with 0.022 × 0.028 in. (0.56 × 0.71 mm) double slot. A 10 mm extension arm was constructed in a 0.019 × 0.025 in. (0.48 × 0.63 mm) stainless steel rectangular wire from the auxiliary tube. Both the tube and extension arm were fixed rigidly. The miniscrew was designed with a head diameter of 1.6 mm. Four miniscrews were placed on the mesial region of the second bicuspid in an apical direction with 2.0 mm vertical interval starting from a height corresponding to the gingival margin of the second molar. All appliance components were exported to AutoCAD format files.

After all components were constructed, these anatomical and appliance elements were imported to CAD software Autodesk Inventor Fusion™ (Version 2013, Autodesk Inc.) and integrated with each other. Anatomical components were initially converted from NURBS surface model to a solid model, and then combined with appliance solid models using a Boolean modelling method (Figure 1). 3D XYZ co-ordinates were constructed by using the anterior edges of the buccal tube model as shown in Figure 2A. As a result, PDL was constructed with 0.25 mm thickness. To evaluate the effect of the length of the extension arm and miniscrew positioning, different loading conditions were simulated. The extension arm was sectioned every 2 mm for the different points of force application (Hook 1–5), and the miniscrews were placed on four different heights (MS 1–4) as shown in Figure 3. Finally, the alveolar bone and the trabecular bone adjacent to the molar were used for the analysis (Supplementary Figure 1).

FE analysis

Before FE analysis, entire models were imported into structural FE analysis software Autodesk Simulation Mechanical™ (Version 2014, Autodesk Inc.) directly and mesh generation was performed. The FE mesh model consisted of 287757 second-order tetrahedral solid elements (Supplementary Figure 1). Table 1 shows all material properties used in this study. All components were considered homogeneous and isotropic materials. A material property of the PDL was assigned based on the data presented by Kojima and Fukui (9).

FE analysis was performed under the condition that the bottom of the cortical and trabecular bone was constrained and 1.0 N protraction force was applied from each segment of the extension

Figure 1. Solid model constructed cone beam computed tomography combined with appliance models.
arm to each miniscrew. A total of 80 loading combinations were analyzed by changing the length of the extension arm (Hook 1–5), the height of the miniscrew (MS 1–4), and the magnitudes of protraction force on the lingual side (0, 0.5, 1.0, and 1.5 N). The lingual force was given directly from a lingual centre point of second molar crown to a lingual centre point of second bicuspid crown (Supplementary Figure 2). The type of molar movement caused by the initial force in each condition was evaluated. The loading conditions that resulted in molar translation were considered ideal.

Measurement

Three nodes—the tip of the mesiolingual cusp, the tip of the mesiobuccal cusp, and the apex of the distal root—were selected for evaluating the initial movement of the molar. Initial movement was determined on each X–Z, Y–Z, and X–Y plane according to the changes of these three nodes (Figure 2). The molar displacement is a complex movement, which combines linear and rotational effects at the centre of resistance. To find the best way to achieve translation (prevent unfavourable rotation caused by the traction force), we determined only the rotational effects at the centre of resistance in this study. Rotation on the X–Z plane was labelled as mesiodistal tipping (MD tipping), rotation on the Y–Z plane was labelled as buccolingual inclination (BL tipping), and rotation on the X–Y plane was labelled as rotation. In this study, counter-clockwise rotation on each plane was considered as a positive value.

Results

Figure 4 depicts the three types of molar movement, MD tipping, BL tipping, and rotation, under the condition of a labial force from the molar to MS 1 without lingual traction force. As the length of the extension arm increased from Hook 1 to Hook 5, MD tipping and rotation decreased by 0.8 and 0.18 degrees, respectively (Figure 4A). In fact, translatory movement was observed with Hook 4 (8 mm) and slight distal tipping with Hook 5 (10 mm). On the other hand, less change was observed in BL tipping, which remained constant as a buccal tipping tendency.

The same linear trends were observed in the other loading conditions that included a lingual traction (Figure 4B–4D). However, the rotational tendency progressively decreased as the lingual traction force increased, up to a negligible degree with a force magnitude of 1.5 N (Figure 4D). On the other hand, as expected, the amount of MD tipping increased with the addition of a lingual force. Thus, translatory movement of the molar was not observed with the addition of a lingual force. However, the addition of a lingual force also

Figure 2. Three-dimensional (3D) XYZ co-ordinates. (A) 3D XYZ co-ordinates using anterior edges of buccal tube model. (B) The rotation on the X–Z plane considered as mesiodistal tipping (MD tipping). (C) The rotation on the Y–Z plane considered as buccolingual inclination (BL tipping). (D) The rotation on the X–Y plane considered as rotation.

Figure 3. (A) Details of five traction hooks and (B) details of four miniscrews.

Table 1. Material properties used in the simulations.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buccal tube with traction arm</td>
<td>200 000</td>
<td>0.3</td>
</tr>
<tr>
<td>Periodontal ligament</td>
<td>0.13</td>
<td>0.45</td>
</tr>
<tr>
<td>Molar</td>
<td>20 000</td>
<td>0.3</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>13 700</td>
<td>0.3</td>
</tr>
<tr>
<td>Trabecular bone</td>
<td>1 370</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Figure 4. Molar movement under the condition of loading in the direction of MS 1. (A) Buccal 1.0 N loading without lingual force. (B) Buccal 1.0 N loading with 0.5 N lingual force. (C) Buccal 1.0 N loading with 1.0 N lingual force. (D) Buccal 1.0 N loading with 1.5 N lingual force.
contributed to the reduction of the buccal tipping tendency (3D displacement of the molar on each plane is visualized in Supplementary Figure 3).

Figure 5 shows the molar displacement with the loading condition that involved the different extension arm heights to MS 2. Same trends were observed in all situations including lingual traction. Figures 6 and 7 also show the molar movement with the labial force directed to MS 3 and MS 4, respectively. In all loading situations, the trend of these two conditions was almost the same as shown in Figures 4 and 5.

A comparison of the 3D molar movement based on the different heights of the miniscrews is summarized in Figure 8. A labial constant loading condition from Hook 5 to all miniscrew heights was analyzed with 1.0 N lingual traction force. It was observed that as the height of the miniscrew progressed apically, MD tipping and rotation increased slightly. In contrast, BL tipping decreased slightly with a more apical position of the miniscrew.

Discussion

FE method, originally designed for engineering modelling, is now commonly used in dentistry to analyse materials and loading conditions. In orthodontics, FE method has been used to clarify the stress distribution causing root resorption (17), to evaluate the risk of adverse events during technical procedures (18), and to verify and devise new mechanics (12, 15, 19, 20). Orthodontic treatment requires adequate management of the mechanics and attention to biology in order to achieve efficient tooth movement. Recently, FE analysis has provided a visual image of the effects of an orthodontic force on the tooth and its supporting structures. Furthermore, it serves as a useful tool to simulate different loading systems and evaluate the initial effects in the dentoalveolar structures to better understand biomechanics.

It could be argued that in the current experimental setup, a 2D analysis of vector mechanics could have yielded similar results. However, as there is a shift in orthodontics to a 3D analysis, a FE analysis that provides specific details in all dimensions was used. Furthermore, a determination of a single centre of resistance is unlikely as a result of tooth morphology. In fact, Viecilli et al. (21) concluded that geometric asymmetry of the tooth and PDL implies axes of resistance that do not intersect; hence, the axes do not define the centre of resistance as a 3D point. This may show the difficulty in determination of centre or axis of rotation and limitation of conventional 2D theory for 3D mechanics. In other
words, actual changes, like 3D rotation, can be determined only by 3D analysis.

In a FE simulation study, the setup parameters are critical to accomplish a realistic simulation and reliable results. However, some material behaviours are difficult to model. In fact, the material property of the PDL has not yet been fully clarified. Fill et al. (22) published a literature review of the PDL mechanical properties and highlighted that the elastic component is non-linear with anisotropic characteristics, in which collagen fibres are a key behavioural factor. Toms et al. (23) suggested a quasi-linear viscoelastic behavior of the human PDL based on frozen human specimens; however, the behavior of extracted specimens may be different from that found clinically. In contrast, Kojima and Fukui (9) investigated both linear and non-linear conditions of the PDL and stated that tooth movements within a load of 2.5 N, for both conditions, yielded similar results despite considerable differences in the elastic moduli. Van Schepdael et al. (24) also found that although the PDL is a non-linear and anisotropic material with a time-dependent hysteresis behavior, the location of the centre of resistance and the centre of rotation can be approximated within the margins of clinical results by assuming the PDL as a linear, isotropic material. Therefore, the PDL was assumed as linear and elastic homogeneous isotropic structure in this study.

Figure 4 depicts how the length of the extension arm was an important determinant in the amount of MD tipping. As the arm increased in length, MD tipping decreased gradually. This is consistent with the findings of Ammar et al. (11) who evaluated the effects of orthodontic bracket hook length and force angulation on the resulting stress response on PDL during lower canine retraction using miniscrews. They found that as the hook length increased from 0 to 7 mm apically along the root of the canine, stress magnitudes in the PDL were significantly reduced and also more uniform along most of the evaluated regions.

The location of the centre of resistance of a multi-rooted tooth, on a sagittal (X–Y plane) view has been suggested to be 1–2 mm apically from the furcation (25, 26). In this study, the furcation was located between Hooks 3 and 4. The results showed the least MD tipping with loading condition for Hook 4, which approximates the location of the predicted centre of resistance. Furthermore, the height of Hook 5 was located further apically, resulting in slight distal tipping.

In contrast, BL tipping was minimally affected despite of the changes in hook length. This could be explained by the small variation of the perpendicular distance from hook to a centre of resistance on the Y–Z plane with increasing hook length. Because the labial force remained constant, similar moments were generated by the buccal force at every arm length height. For the same reason, rotation also remained constant despite the changes of hook length.

Mesial rotation was observed regardless of the length of the extension arm. To prevent rotation, which is considered a side-effect, we applied a lingual force from a single point. As expected, the larger the lingual traction force, the less rotation was found. However, even though the force magnitudes were equal from the buccal and lingual side, rotation was still observed. Furthermore, a slight mesial-in rotation was still found with 1.5 N lingual force (Figure 4D). This could be explained by the location of the centre of resistance from the occlusal (X–Y plane) view, which has been assumed to be located about a mid-point on the occlusal surface. From this expected centre of resistance, the perpendicular distance to the extension arm on the labial was 7.3 mm, whereas the perpendicular distance to the lingual force was 4.6 mm. Moreover, Figure 4D shows how translation was observed from the occlusal view with a loading condition from Hook 5 to MS 1, and a 1.5 N lingual force. With this loading condition, the ratio of the distance from centre of resistance to the buccal and lingual loading points was approximately 3:2. This ratio further supports that the location of a centre of resistance (in the X–Y plane) in this study was around a midpoint on the occlusal surface. From a clinical perspective, as the lingual force needs to be higher in magnitude than the buccal force to minimize rotation, reducing the magnitude of the labial force should be considered to prevent anchorage loss because the lingual force is often attached to an anterior tooth and not a miniscrew.

However, traction force from the lingual side generates both decreased rotation and increased MD tipping. Extending an arm apically from the lingual side may be the best option to control rotation and reduce mesial tipping. However, this option adds further clinical complexity for the delivery of the mechanics and may negatively impact patients’ comfort. Based on this clinical viewpoint, we gave a lingual protraction force from the crown of the molar to the crown of the second bicuspid using lingual buttons.

Figure 8 showed the difference of the molar displacement with varying miniscrew heights. More occlusal placement of the miniscrews caused a lesser degree of MD tipping and rotation. On the other hand, BL tipping was increased with a more occlusal position of the miniscrew. However, the variation with the different heights was minimal. This indicated that the height of miniscrews was not critical in affecting the type of tooth movement.

From a clinical perspective, most orthodontists use brackets and wires for orthodontic treatment. It is clear from our model that molar protraction mechanics significantly benefits from an archwire in order to counteract the moment of the forces especially in the first and second order. Applying forces from extension arms to a specific length to prevent tipping may not be possible in some patients due to anatomic limitations such as the depth of the labial sulcus. However, it is unclear what specific archwire dimension is necessary to counteract these rotation and tipping tendencies. Length of the edentulous space, geometry of the brackets adjacent to the edentulous site, archwire and bracket materials, saliva and occlusion and their effect on friction are all factors that need to be considered. All these variables make it difficult to model this clinical situation with accuracy when an archwire is included. Although the model described in this study may not match exactly the clinical situation, it does provide the clinician with important information of how rotational tendencies around
all axes are generated in molar protraction; thus, it can help clinicians understand how these can be controlled with or without an archwire present. Further studies aimed to find reasonable parameters useful for the analysis of molar protraction from miniscrews with continuous archwire conditions will be needed for better understanding the biomechanics involved in this complex orthodontic movement. These studies may be able to provide information on how these rotational tendencies may increase friction in the archwire and thus result in side-effects in the teeth anterior to the edentulous site.

Conclusions

1. In this specific FE model of mandibular molar protraction, a long extension arm (8–10 mm) was necessary to eliminate mesial tipping when a protraction force was applied.
2. The addition of lingual force is helpful to control rotation; however, at expense of added mesial tipping.
3. The most ideal force system in the model appeared to be the longest extension arm (10 mm) and the addition a lingual force half or equal magnitude of the labial force (0.5–1 N).
4. The height of the miniscrew was not critical to achieve translation during mandibular molar protraction; although, a more occlusal position of a miniscrew may help reduce mesial tipping with a long extension arm.

Supplementary material

Supplementary material is available at European Journal of Orthodontics online.

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References