Original article

Effects of palate depth, modified arm shape, and anchor screw on rapid maxillary expansion: a finite element analysis

Yosuke Matsuyama, Mitsuru Motoyoshi, Niina Tsurumachi and Noriyoshi Shimizu

Department of Orthodontics, Nihon University School of Dentistry, Tokyo, Japan

Correspondence to: Mitsuru Motoyoshi, Department of Orthodontics, Nihon University School of Dentistry, 1-8-13 Kanda-surugadai, Chiyoda-ku, Tokyo 101-8310, Japan. E-mail: motoyoshi.mitsuru@nihon-u.ac.jp

Summary

Objectives: This study examined the effects of palate depth, modifications of the arm shape, and anchor screw placement in the mid-palatal area on rapid maxillary expansion (RME) using finite element (FE) analysis.

Materials and Methods: Three-dimensional FE models were constructed that included the maxilla (cortical and cancellous bone), maxillary sinus, maxillary first molar and first premolar, periodontal membrane, and an RME appliance with arms, bands, and anchor screws. The expansion screws were activated 0.2 mm transversely.

Results: The deepest palate model had the smallest lateral displacement of the tooth and expansion of the mid-palatal suture and the greatest strain of the arm among the models with different palate heights. The model with a larger diameter arm had the smallest arm strain among the models with various arm shapes. The model with an anchor screw had the greatest lateral displacement of the tooth and expansion of the mid-palatal suture among all models.

Conclusions: For a deeper palate, the arm strain increased and the effect of RME decreased. Modified arm shapes such as a larger diameter arm, arms connected by a diagonal wire, a straight arm, and a shorter arm efficiently expanded the maxillary dental arch. Anchor screws increased the effect of RME, generated more and closer bodily movement of the tooth, and parallel expansion of the mid-palatal suture. The model with an anchor screw without arms decreased the displacement of the teeth compared to the models with arms, so the arms are necessary for effective RME.

Introduction

In orthodontic treatment, rapid maxillary expansion (RME) is generally used to expand the arch and mid-palatal suture and split the mid-palatal structure in juveniles and correct transverse maxillary deficiencies and arch-length discrepancies (1, 2). Clinically, however, we suggest that RME often does not act effectively in the high-arched palate and the expansion is smaller posteriorly than anteriorly. The maxilla, teeth, and hyrax expander were modelled according to Araujo et al. (3), and a force of 1 N was applied in a direction normal to the medial surface of the body of the apparatus. When a screw is located palatal to the centre of resistance of the maxillary first molars, the crown tends to tip in the lingual direction. According to Wertz (4) and Timms (5), at the level of the mid-palatal suture, the separation was wider anteriorly at the anterior nasal spine (ANS) and decreased significantly towards the posterior part of the suture, close to the horizontal part of the palatine bone. To maintain the force of RME deeper in the palate, it is thought that the arm shape should be changed to reduce the strain. Therefore, we examined the outcome of RME according to the difference in the depth of the palate and the effect of the shape of the arm on the force of RME deeper in the palate.
We also aimed to determine whether an anchor screw effectively widened the posterior area of the mid-palatal suture and the maxillary arch (see online supplementary figure 1). The use of an anchor screw is widespread in clinical orthodontics because this device is simple, minimally invasive surgically, easy to apply clinically, easy to remove, reasonably priced, and allows immediate loading and results in favourable primary stability and retention (6–8). Anchor screws have been placed in the mid-palatal area with encouraging results, and recent studies have reported high success rates (90.8–95.6 per cent) (9, 10). Especially for young patients whose palatal suture is immature, the mid-palatal area is hard tissue suitable for maintaining the stability of the anchor screw (11, 12). RME is applied in young patients in most cases, so RME with an anchor screw in the mid-palatal area is assumed to be effective and stable.

This study examined the effect of modifications of the arm shape deeper in the palate and the effect of an anchor screw on the force in the mid-palatal area. The maxillary bone, first molars, first premolars, RME, bands, and anchor screws were reproduced using three-dimensional (3D) finite element (FE) models. The effects of palate depth, arm shape, and anchor screws in the mid-palatal area on RME were examined.

Materials and methods
Preparation of FE models
FE models were constructed that included the maxilla (cortical and cancellous bone), maxillary sinuses, maxillary first molar and first premolar, periodontal membrane, and RME appliance with 1.5 mm diameter arms, bands, and anchor screws (Figure 1) using a 3D computer-aided design program (SolidWorks 2012; SolidWorks Japan, Tokyo, Japan). A standard FE model of the maxilla was constructed (model A), based on digitized 1 mm computed tomography slices of a human phantom from the Department of Orthodontics at Niho University School of Dentistry. The depth of the palate was based on published data (13, 14). The forms of the maxillary first molar and first premolar were constructed with reference to Ash (13).

Two models (models B and C) were constructed by modifying model A. Models B and C had a palate that was 4 and 8 mm higher than in model A, respectively (Figure 2). An additional four models (models D to G) based on model C were made with various arm shapes (Figure 2). In model D, the diameter of the RME arm was increased from 1.5 to 2 mm. In model E, the arms were connected with a diagonal wire. In model F, the arms were straight. In model G, the shape and length of the arm was equal to that in model A, while the depth of the palate equalled that in model C. The last two models (models H and I) included anchor screws (Figure 3). In model H, four anchor screws were placed lateral to the mid-palatal suture and connected to the expansion screw. In model I, the band and arm of the RME device were removed from model H, and the expansion screw was connected to the palatine bone using the anchor screws.

The bone, teeth, periodontal membrane, RME appliance, bands, and anchor screws were assumed to be homogeneous, isotropic, and linearly elastic and the solution was determined with a static analysis. The material properties of the elements in all models were based on published data (Table 1) (15–19). The periodontal ligament was 0.2 mm thick and the mid-palatal suture 0.5 mm (20, 21). The material properties of the mid-palatal suture were assumed to be mature, as in a 16-year-old (19). Each model was meshed automatically using SolidWorks. Table 2 shows the number of nodes and elements in each model.

Boundary condition and solution
The nodes at the surface of the zygomatico-maxillary suture, naso-maxillary suture, and pterygomaxillary connection elements were restricted to three degrees of freedom (X, Y, and Z). The expansion screws were activated 0.2 mm transversely. To evaluate the initial stress distribution and displacement of the models, one quarter rotation of the screw (approximately 0.2 mm of expansion) was used in this simulation. For the FE analysis, a personal computer (CPU, Celeron 2.20 GHz; hard disk, 40.0 GB; random access memory, 1024 MB) and FE program (COSMOS/Works 2012) were used. The displacement of the teeth and expansion of the mid-palatal suture were evaluated. The buccal cusp and apex of the buccal root of the first premolar and the mesiobuccal cusp and apex of the mesiobuccal root of the first molar were used as reference points to evaluate tooth displacement. The amount of expansion resulting from RME activation was measured at two points: the anterior (ANS) and posterior (PNS) nasal spines of the mid-palatal suture. The simulated stresses in all models for all components were von Mises stresses. The strain was expressed as an equivalent strain (ESTRN), where 
\[ \varepsilon_{\text{estrn}} = 2\left(\varepsilon_x + \varepsilon_y + \varepsilon_z\right)/3 \]
and
\[ \varepsilon_x = 0.5\left(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}\right) \]
\[ \varepsilon_y = 0.5\left(\varepsilon_{xy} + \varepsilon_{yx} + \varepsilon_{yz} + \varepsilon_{zy}\right) \]
\[ \varepsilon_z = 0.5\left(\varepsilon_{xz} + \varepsilon_{zx} + \varepsilon_{yz} + \varepsilon_{zy}\right) \]
\[ \varepsilon = \sqrt{\varepsilon_x^2 + \varepsilon_y^2 + \varepsilon_z^2} \]
The expanse strain in the YZ plane, GMXZ is the shear strain in the X direction on the YZ plane, GMYZ is the shear strain in the Z direction on the YZ plane, and GMYZ is the shear strain in the Z direction on the XZ plane.

Results
Tooth displacement
Figure 4 shows the lateral displacement of the first premolar and first molar in models A to I.

Models A, B, and C
The lateral displacement of the buccal cusp of the first premolar did not differ between models A and B, but decreased in model C. The lateral displacement of the apex of the buccal root of the first premolar in model A was less than in models B and C. The lateral displacement of the mesiobuccal cusp of the first molar decreased
sequentially from model A to C. The lateral displacement of the apex of the mesiobuccal root of the first molar increased sequentially from model A to C.

Models C to I
The lateral displacement of the buccal cusp of the first premolar in models D to G was greater than in model C. The lateral displacement of the apex of the buccal cusp of the first premolar in models D, E, and G was greater than in model C, while models C and F did not differ. The lateral displacement of the mesiobuccal cusp of the first molar in models D, F, and G was greater than in model C, while models C and E did not differ. The lateral displacement of the apex of the mesiobuccal root of the first molar did not differ among models C to G.

The lateral displacement of the buccal cusp of the first premolar and the mesiobuccal cusp and apex of the mesiobuccal root of the first molar in model H was greater than in model C, while it decreased in model I. The lateral displacement of the apex of the buccal root of the first premolar in models H and I was more than in model C.

Expansion of the mid-palatal suture
Figure 3 shows the lateral expansion of the mid-palatal suture in models A to I.

Models A, B, and C
The lateral expansion of ANS and PNS of the mid-palatal suture decreased sequentially from models A to C. The lateral expansion of PNS of the mid-palatal suture was less than that of ANS in models A to C.

Models C to I
The lateral expansion of ANS of the mid-palatal suture in models D to G was greater than in model C. The lateral expansion of PNS of the mid-palatal suture did not differ markedly among models C to G. The lateral expansion of ANS and PNS of the mid-palatal suture in models H and I was greater than in model C.

Strain of the arm
Figure 6 shows the strain in the arms in models A to H.

Models A, B, and C
The strain in the arms connected to the first premolar and first molar increased gradually from model A to C. The strain of the arms connected to the first molar was highest in model C.
The strain in the arms connected to the first premolar and first molar in models D to H was less than in model C.

Stress distribution
Figure 7 shows the von Mises stress distribution in the occlusal view of models A to I.

Models A, B, and C
In models A to C, stresses exceeding 9.0 MPa were seen in the areas of the zygomaticoalveolar line, pterygomaxillary connection, and posterior alveolar bone, while stresses less than 2.5 MPa were seen in the posterior hard palate, mid-palatal suture, and anterior alveolar bone.

Models C to I
In models C to G, stresses exceeding 9.0 MPa were seen in the vicinity of the zygomaticoalveolar line, pterygomaxillary connection, and posterior alveolar bone, while stresses less than 2.5 MPa were seen in the vicinity of the posterior hard palate, mid-palatal suture, and anterior alveolar bone.

In models H and I, stresses exceeding 10.0 MPa were seen in the vicinity of the zygomaticoalveolar line, pterygomaxillary connection, and posterior hard palate, and stresses less than 2.5 MPa were seen in the vicinity of the mid-palatal suture, anterior alveolar bone, and teeth.

Discussion
The FE method (FEM) is a standard tool used in engineering to precisely assess local stress, strain, and displacement in geometrically complex structures (22). According to Araugio et al. (3), the FEM has been used successfully to evaluate the forces and deformations imposed on teeth and craniofacial bones when RME is used. Lee et al. (18) reported that the 3D FEM is a valid method for analysing complex craniofacial structures. The FEM enables the simulation of clinical orthodontic forces and the study of biomechanical variables induced in living structures by various external forces in 3D space (22).

The initial effects of RME can be evaluated using the FEM. This study provides useful information on the difference in the effect of RME according to the depth of the palate, shape of the arms, and presence of anchor screws.

With a deeper palate, the displacement of the crown of the maxillary first molar and first premolar decreased, while the displacement of the root increased and the expansion in the median palatine suture decreased (Figures 4 and 5). With a deeper palate, the arm was longer and the strain on the arm increased (Figure 6). The decrease in the effect of RME was thought to be caused by the strain on the arms. Therefore, it was necessary to reduce the strain on the arms for effective RME. To stiffen the arms, we constructed four models in which the shapes of the arm were modified by increasing the diameter, connecting them with a diagonal wire, designing a straight arm, and shortening the arm length. All of these modifications decreased the strain on the arms and increased the displacement of the teeth and expansion of the mid-palatal suture, even for deeper palates (Figures 4–6). A shortened arm had the greatest effect on the transverse displacement of the teeth crown. This was followed in order by increasing the diameter of the arm, making a straight arm, and connecting the arms with a diagonal wire (Figure 4). The order of the effect was thought to be caused by the position of the expansion screw and the difference in the arm strain. However, the increase in the expansion of the mid-palatal suture was small in these models (Figure 5).

According to Araugio et al. (3), the construction of the hyrax expander apparatus with an expansion screw located occlusal to the centre of resistance of the maxillary first molar generated an increased tendency toward buccal tipping of the crown. However, when the expansion screw is located palatal to the centre of resistance of the maxillary first molars, the crown tends to tip in the lingual direction (3). When the expansion screw was placed far from the centre of resistance, the apices were displaced in the opposite direction from the crowns (3). To ensure effective lateral displacement of the teeth,
the expansion screw should be located at the height of the centre of resistance of the first molar. This, however, makes the tongue feel odd. It is necessary to let the RME comply with the palate to avoid exercise restrictions and this odd feeling of the tongue.

The expansion of the mid-palatal suture was less posteriorly than anteriorly (Figure 5). As a result, the mid-palatal suture showed V-shaped expansion. In agreement with our results, Akkaya et al. (23) and Wertz (4) reported that transverse expansion was greater anteriorly. The zygomaticoalveolar line and pterygomaxillary sutures suppressed the expansion of the posterior area of the mid-palatal suture (Figure 7). Stresses exceeding 9.0 MPa were seen in the vicinity of the zygomaticoalveolar line, pterygomaxillary sutures, and posterior alveolar bone. This stress is sufficient to transform a bone (2). Chaconas and Caputo (24) showed that the mid-palatal and pterygomaxillary sutures are the primary anatomic resistance to expansion. Lagravère et al. (25) concluded that more expansion posteriorly was achieved by surgically assisted expansion. Consequently, when the forces are applied directly to the posterior palate, the mid-palatal suture would expand in parallel.

We constructed a model with four anchor screws to apply the forces to the palate directly. As the forces can be applied directly to the basal bone by using anchor screws, the skeletal RME should increase. According to Lee et al. (2), bone-borne expanders with anchor screws are a viable treatment option. Karakgiolidou et al. (26) reported excellent performance of anchor screws placed in the paramedian area of the anterior palate in conjunction with various orthodontic appliances for distinct orthodontic treatment needs.

To apply forces directly to the palate, we constructed FE models of RME with anchor screws. With anchor screws, the effects of RME increased and the mid-palatal suture was widened both anteriorly and posteriorly, even with a deeper palate (Figure 5). Therefore, the mid-palatal suture showed parallel expansion. According to Lee et al. (2), transverse expansion of the mid-palatal suture occurred largely in the posterior area in the models with four anchor screws. The difference between their study and ours can be explained by the difference in the material properties of the mid-palatal suture. Lee et al. (2) used a greater Young’s modulus of the mid-palatal suture than we did. Moreover, the forces might be loaded directly onto the posterior palate because the posterior part has thinner cortical bone than anterior, as Lee et al. (2) described.

Lee et al. (2) concluded that the most efficient position for the anchor screws was in the palatal slopes, which was thought to be more effective than lateral to the mid-palatal sutures when RME without the arm is applied. Anchor screws increased the effect of RME, and generated more and closer bodily movement of the tooth. In the model of RME with anchor screws without the arms, tooth displacement decreased, except for the root of the first premolar (Figure 4). This suggests that the arms are necessary for effective expansion in addition to a bone-borne expander, when placing anchor screws near the suture.

Conclusions
1. As the palate deepened, the arm strain increased and the effect of RME decreased.
2. Modified arm shapes, such as a larger diameter arm, arms connected by a diagonal wire, a straight arm, and a shorter arm, promoted expansion of the maxillary dental arch.
3. Anchor screws increased the effect of RME, and generated more and closer bodily movement of the tooth together with parallel mid-palatal suture expansion. By contrast, in the design without arms, the tooth displacement decreased; therefore, the arms are necessary for effective RME when placing anchor screws near the suture.

Supplementary material
Supplementary material is available at European Journal of Orthodontics online.

References


