Original article

Displacement and stress distribution of the maxillofacial complex during maxillary protraction with buccal versus palatal plates: finite element analysis

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Summary

Objectives: The aim of this study was to analyse the displacement and stress distribution in the maxillofacial complex during maxillary protraction with buccal and palatal plates using three-dimensional finite element analysis.

Materials and methods: Three anchorage appliance models—palatal plate (Type A), miniplate at the infrayzygomatic crest (Type B), and conventional tooth-borne appliance (Type C)—were designed and integrated into a skull model. Protraction force was 500g per side and force direction was forward and 30 degree downward to the maxillary occlusal plane. The stress distribution around the circum-maxillary sutures and the displacement of the surface landmarks were analysed.

Results: All models showed forward and upward displacement at anterior nasal spine, Point A, and prosthion and forward and downward displacement at posterior nasal spine resulting in a counter-clockwise rotation. This anterior displacement was greatest in Type A. At the maxillary process of the zygoma, upward movement was shown only in Type A, whereas downward movement was observed in Types B and C. The greatest stresses in Type A were at the pterygomaxillary and the zygomaticotemporal sutures. Type B showed the greatest stress at the frontomaxillary suture.

Limitations: Type A showed asymmetric results; however, it was not of clinical significance.

Conclusion: The palatal plate resulted in wider stress distribution and more forward displacement compared to miniplate at the infrayzygomatic crest area and conventional tooth-borne appliances. It might be recommended to consider the application of the palatal plate for maxillary protraction in Class III patients.
Introduction
Maxillary protraction with a facemask and tooth-borne anchorage has been the conventional treatment for growing Class III patients with maxillary deficiency. This treatment modality results in forward displacement of the maxilla, forward movement of the maxillary molars and incisors, extrusion of the maxillary molars and clockwise rotation of the mandible (1–4). Therefore, several skeletal anchorage systems have been proposed to maximize the skeletal effect of maxillary protraction and decrease undesirable dental effects (5–10).

Several investigators have placed miniplates in the infrazygomatic crest area and the lateral nasal wall as an anchorage for maxillary protraction (11–16). However, the miniplates require invasive flap surgery for placement and removal of the plate and may cause soft tissue irritation.

The palate has been identified as a safe skeletal anchorage area in orthodontic treatment with a high success rate (17–19). In addition, its bone thickness and density and soft tissue thickness have been shown to be sufficient to withstand placement of temporary skeletal anchorage devices (TSADs), even in adolescents and younger children (20–23). Palatal plates can be placed easily under local anaesthesia due to the flapless surgery and good accessibility. Kook et al. (24, 25) have placed palatal plates to achieve maxillary total distalization in adults and adolescents. Recently, a modified palatal plate has been applied for maxillary protraction with a facemask (Figure 1; Kook, Bayome, Kim, and Chung, manuscript in preparation).

Three-dimensional (3D) finite element analysis has been applied to simulate maxillary protraction and evaluate the displacement and stress distribution of the maxillofacial complex (26–28). Yan et al. (29) compared the differences between skeletal and dental anchorages in maxillary protraction. However, no study has evaluated the biomechanical effects of facemask therapy with palatal anchorage.

Therefore, the aim of this study was to analyse the displacement and stress distribution in the maxillofacial complex during maxillary protraction with a palatal plate, miniplate at infrazygomatic crest area, and conventional tooth-borne appliance using 3D finite element analysis.

![Figure 1. Modified palatal plate for maxillary protraction using a facemask. (A) Palatal plate with miniscrews. (B) Elastics connected to the facemask.](image)

Materials and methods
Construction of the finite element model
A computer-aided design model was constructed from a computed tomography image of a dry skull using MIMICS version 15.01 (Materialise, Leuven, Belgium). The geometry of this anatomical model was imported using Visual-mesh V 7.0 software (ESI Group, Paris, France) to generate a tetrahedral finite element mesh. The maxilla including the teeth and alveolar bone were constructed of 1 mm tetrahedrons, while the rest was constructed of 5 mm tetrahedrons. The mechanical properties of cortical bone, cancellous bone, tooth, miniplates, miniscrews, stainless steel (SS) wires, periodontal ligament, and sutures in the 3D finite element model are shown in Table 1 (16, 26, 30–33) The thickness of the cortical bone was modelled according to a study by Farnsworth et al. (34); the thickness of the periodontal ligament was 0.2 mm (35), and the width of the midpalatal suture and other maxillofacial sutures was 0.5 mm (36).

Boundary condition
The foramen magnum was fixed and used as the origin point as suggested by Gautam et al. (37). The forehead was in contact with a fixed band (see online supplementary figure 1). The 3D co-ordinates were the X plane, sagittal plane; Y plane, transverse plane; and Z plane, vertical plane. Positive values indicate forward, inward, and upward displacements on the X, Y, and Z planes, respectively.

Design of the appliance
Three-dimensional finite element models of three appliances transmitting the orthopaedic force to the maxilla: palatal plate (Type A), miniplate at the infrazygomatic crest (Type B), conventional tooth-borne appliance (Type C) were made based on 3D data (Figure 2). These models were integrated to the skull model by the projection method.

Type A appliance consisted of a palatal miniplate with three hooks on each arm (thickness, 0.80 mm; width, 2.0 mm; half side length, 28.0 mm; palatal plate, Jeil Medical, Seoul, Korea). The palatal plate was fixed to the palate with three miniscrews (diameter, 2 mm; length, 8 mm) into the screw tubes (2 mm in diameter) 2 mm apart from midpalatal suture. The distal end of the palatal plate was placed between the canine and first premolar, equivalent to the gingival level.

In Type B, a curved miniplate with six holes (thickness, 0.80 mm; length, 31.65 mm; holes diameter, 2 mm; LeFort system, Jeil Medical Co., Seoul, Korea) was placed on the infrazygomatic area using the same type of miniscrews as in Type A, with the distal end of the miniplate placed 2 mm apical to the gingival crest of the alveolar bone between the canine and first premolar.

In Types A and B, the miniscrews were rigidly connected to bone by sharing nodes, as the stress around the miniscrews was not the aim of this study.

Table 1. Young's modulus and Poisson's ratio for materials of the models

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's modulus (N/mm²)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone</td>
<td>$1.34 \times 10^5$</td>
<td>0.30</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>$0.78 \times 10^5$</td>
<td>0.30</td>
</tr>
<tr>
<td>Miniplate</td>
<td>$10.30 \times 10^5$</td>
<td>0.33</td>
</tr>
<tr>
<td>Miniscrew</td>
<td>$10.30 \times 10^5$</td>
<td>0.33</td>
</tr>
<tr>
<td>Suture</td>
<td>$68.65$</td>
<td>0.40</td>
</tr>
<tr>
<td>Tooth</td>
<td>$2.03 \times 10^5$</td>
<td>0.30</td>
</tr>
<tr>
<td>Stainless steel wire</td>
<td>$20.59 \times 10^5$</td>
<td>0.30</td>
</tr>
<tr>
<td>Periodontal ligament</td>
<td>$50.01$</td>
<td>0.49</td>
</tr>
</tbody>
</table>
Type C had a conventional tooth-borne anchorage; first premolars and first molars were banded and connected with 0.9 mm (0.04 inches) SS round wire at both buccal and lingual sides. First premolars and first molars were connected to the contralateral sides using the same size SS wire in the form of a transpalatal arch. A protraction hook was attached to the band of the first premolar with the distal end 2 mm above the gingival crest of the alveolar bone between canines and first premolars.

Protraction and analysis
A protraction force of 500g was applied per side at the hooks of the appliances in a forward and 30 degree downward vector to the maxillary occlusal plane to minimize anticlockwise rotation caused by maxillary protraction below centre of resistance (see online supplementary figure 2) (38). Stress distribution and displacement of the landmarks in the maxillofacial bone were analysed. The suture points and the surface landmark in the maxillofacial bone are shown in Figure 3. PAM-MEDYSA V 2011 software was used for solving and Visual-Viewer 7.0 for post-processing (ESI Group, Paris, France).

Results
Displacement
The right and left sides of both Types B and C showed symmetric results. Type A presented slight asymmetry in the displacement results due to the asymmetric shape of the palatal plate appliance. However, this was not pronounced on the stress distribution.

In the sagittal plane, all landmarks were displaced anteriorly in the three types, except for the left frontal process of the maxilla (Type A), where the displacement was slightly posterior. The anterior displacement was greater in the posterior teeth than in the anteriors, and in the inferior landmarks than in the superiors. Type A showed more anterior displacement at the inferior landmarks and less at the superior ones than Types B and C (Table 2 and Figure 4).

In the vertical plane, Type A showed downward displacement at the frontal process of the maxilla, temporal process of zygoma, posterior nasal spine (PNS), and second molars. It demonstrated upward movement in the other skeletal landmarks, anterior teeth, premolars, and left first molar area. Upward displacement was highest at prosthion, and downward displacement was highest at PNS and both movements decreased upward. Types B and C showed upward displacements at prosthion, Point A, and anterior nasal spine (ANS), and downward displacements at all other skeletal landmarks. The

Figure 2. Designs of maxillary protraction appliances: palatal plate (A); miniplate at the infrayzygomatic crest (B); conventional tooth-borne appliance (C and D).

Figure 3. (A) Skeletal landmarks: 1, frontomaxillary suture; 2, frontal process of maxilla; 3, inferior orbital rim; 4, ANS; 5, Point A; 6, prosthion; 7, pterygomaxillary suture; 8, zygomaticofrontal suture; 9, frontal process of zygoma; 10, maxillary process of zygoma; 11, zygomaticomaxillary suture; 12, temporal process of zygoma; 13, zygomaticotemporal suture. (B) Dental landmarks: yellow dot, FA point of each tooth; red dot, root point of each tooth.
Table 2. Displacement of skeletal and dental landmarks in the three types under the application of the protracting force (unit = μm).

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Palatal plate type (A)</th>
<th>Buccal plate type (B)</th>
<th>Conventional type (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>Frontal process of maxilla</td>
<td>0.14 0.82 -0.61</td>
<td>-0.01 -0.96 -0.79</td>
<td>0.77 -0.12 -0.55</td>
</tr>
<tr>
<td>Frontal process of zygoma</td>
<td>0.29 0.62 0.37</td>
<td>0.70 -1.08 0.00</td>
<td>0.80 0.58 -0.73</td>
</tr>
<tr>
<td>Inferior orbital rim</td>
<td>1.82 0.78 0.55</td>
<td>1.90 -1.49 0.00</td>
<td>2.11 -0.07 -0.37</td>
</tr>
<tr>
<td>Temporal process of zygoma</td>
<td>2.43 0.56 -0.73</td>
<td>2.99 -0.66 -0.79</td>
<td>1.79 0.48 -0.85</td>
</tr>
<tr>
<td>Maxillary process of zygoma</td>
<td>3.32 0.07 0.61</td>
<td>3.82 -0.55 0.18</td>
<td>2.84 -0.23 -0.67</td>
</tr>
<tr>
<td>ANS</td>
<td>3.49 -0.25 0.55</td>
<td>2.49 -1.12 0.18</td>
<td>3.07 0.00 0.49</td>
</tr>
<tr>
<td>Point A</td>
<td>4.27 -0.72 0.67</td>
<td>3.20 -0.81 0.31</td>
<td>3.47 0.02 0.61</td>
</tr>
<tr>
<td>PNS</td>
<td>4.50 -0.29 -3.30</td>
<td>3.66 0.21 -3.17</td>
<td>3.56 0.11 -1.77</td>
</tr>
<tr>
<td>Prosthion</td>
<td>5.09 -1.23 1.16</td>
<td>3.97 -0.56 0.79</td>
<td>3.94 0.05 0.85</td>
</tr>
<tr>
<td>FA point central incisor</td>
<td>4.20 -0.50 0.92</td>
<td>5.29 -1.34 1.40</td>
<td>4.04 -0.05 0.85</td>
</tr>
<tr>
<td>FA point lateral incisor</td>
<td>4.47 -0.29 1.04</td>
<td>5.37 -1.49 1.59</td>
<td>4.11 -0.06 0.67</td>
</tr>
<tr>
<td>FA point canine</td>
<td>4.54 -0.24 1.10</td>
<td>5.21 -1.46 1.83</td>
<td>4.08 -0.06 0.49</td>
</tr>
<tr>
<td>FA point first premolar</td>
<td>4.76 0.14 0.92</td>
<td>5.30 -1.68 1.59</td>
<td>4.20 -0.05 0.12</td>
</tr>
<tr>
<td>FA point second premolar</td>
<td>4.96 0.32 0.24</td>
<td>5.42 -1.60 0.85</td>
<td>4.30 -0.07 -0.31</td>
</tr>
<tr>
<td>FA point first molar</td>
<td>5.06 0.53 -0.24</td>
<td>5.44 -1.52 0.18</td>
<td>4.28 -0.10 -0.79</td>
</tr>
<tr>
<td>FA point second molar</td>
<td>5.23 0.81 -0.79</td>
<td>5.55 -1.53 -0.43</td>
<td>4.38 -0.10 -1.28</td>
</tr>
<tr>
<td>Root point central incisor</td>
<td>3.26 -0.72 0.06</td>
<td>4.30 -0.73 0.43</td>
<td>3.49 -0.02 0.37</td>
</tr>
<tr>
<td>Root point lateral incisor</td>
<td>3.44 -0.67 0.18</td>
<td>4.30 -0.74 0.67</td>
<td>3.51 -0.02 0.24</td>
</tr>
<tr>
<td>Root point canine</td>
<td>3.27 -0.76 0.12</td>
<td>3.88 -0.47 0.67</td>
<td>3.32 -0.01 0.06</td>
</tr>
<tr>
<td>Root point first premolar</td>
<td>3.76 -0.52 0.43</td>
<td>4.18 -0.72 0.98</td>
<td>3.55 -0.02 -0.06</td>
</tr>
<tr>
<td>Root point second premolar</td>
<td>4.21 -0.14 0.12</td>
<td>4.60 -0.98 0.67</td>
<td>3.78 -0.24 -0.37</td>
</tr>
<tr>
<td>Root point first molar</td>
<td>4.12 0.14 -0.92</td>
<td>4.65 -0.90 -0.61</td>
<td>3.78 -0.03 -0.92</td>
</tr>
<tr>
<td>Root point second molar</td>
<td>4.33 0.51 -1.59</td>
<td>4.82 -0.91 -1.40</td>
<td>3.91 -0.04 -1.46</td>
</tr>
</tbody>
</table>

Due to symmetric results of Types B and C, only the right side was reported. Positive values indicate forward and upward, while negative values indicate backward and downward displacements on the X and Z planes, respectively. On Y plane, the outward movement was indicated by positive value on the right side and negative value on the left side. For the inward movement, that was vice versa.

Figure 4. Displacement in the X-axis. Type A, palatal plate; Type B, miniplate at infrazygomatic crest; Type C, conventional tooth-borne appliance.
anterior teeth and first premolars moved upward, while second premolars and molars moved downward (Table 2 and Figure 5).

In the transverse plane, in Type A, the left side showed outward movement of all landmarks except the PNS. On the right side, the anterior teeth moved inward, while the posteriors moved outward. However, at root level, only the molars showed outward movement. The superior skeletal landmarks moved outward in a decreasing pattern from the frontal process of maxilla to the maxillary process of zygoma, while the inferiors moved inward in an increasing pattern from the ANS to the prosthion. In Types B and C, the greatest displacement in this plane was in the zygoma; the maxillary process of zygoma showed inward movement, while its temporal and frontal processes moved outward. All maxillary landmarks had outward displacement except the frontal process of the maxilla (in both Types B and C) and inferior orbital rim (in Type B, only). All teeth showed inward movement; however, the amount of transverse displacement in Types B and C were very minimal compared to the movement in other directions (Table 2 and Figure 6).

Stress distribution
The greatest stresses in Type A were around the pterygomaxillary and zygomaticotemporal sutures. They were also greater than those in Types B and C. Type B showed the greatest stress around the frontomaxillary suture, which was greater than those of Types A and C. The least stresses were around the frontozygomatic and zygomaticomaxillary sutures in all types (Table 3).

Type A showed high stress concentrations on the palate and near the hooks resulting in lighter stress transmitted to the first premolar through the PDL. Also, there were high stresses at the nasal bones, the inferior orbital rim, the pterygoid plates and around zygomaticotemporal and pterygomaxillary sutures. In addition, stresses were concentrated on the buccal alveolar margin around the first premolars as a result of the contact between the hooks and the palatal alveolar margin in the corresponding area. There was also a concentration of stresses between the two central incisors (Figure 7).

Type B showed high stresses concentrated around the miniscrews placed on the buccal surface of the maxilla and between the central incisors, as well as around the zygomaticotemporal and pterygomaxillary sutures and the pterygoid plates (Figure 7).

Type C showed high stresses concentrated on the first premolars and first molars, as well as around the zygomaticotemporal and pterygomaxillary sutures and the pterygoid plates (Figure 7).

Discussion
Maxillary protraction using a facemask has been an effective treatment option for growing Class III patients. Conventional toothborne appliances caused undesirable dental effects and the timing for effective treatment was confined to the deciduous or early mixed dentitions (39–42). However, protraction using a skeletal anchored appliance decreased the dental effect and enabled a successful application of the treatment modality in the late mixed or permanent dentition phases (9, 15, 43, 44).

The application of miniplates for protraction of the maxilla at the infrazygomatic crest area or nasal wall area required invasive flap surgeries for placement and removal of the plate. Moreover, the bilateral placement doubles the invasiveness, risks, and cost. Therefore, such a procedure can be considered aggressive, especially for growing patients. On the other hand, the placement of a palatal plate is performed at a single site with no flap or incision with no risk to any vital anatomical structures (24, 25).
Recently, several studies have evaluated the palate as a TSADs site in adolescents. Ryu et al. (21) have assessed the palatal bone thickness and reported that the thickness is sufficient to receive TSADs. Han et al. (20) have evaluated the palatal bone density and reported its suitability for TSADs. Lee et al. (23) have examined the palatal soft tissue thickness and recommended the anterior paramedian area as a site for skeletal anchorage. Therefore, the palate can be considered a suitable site for placing TSADs in growing patients.

In our study, all models showed forward and upward displacement at ANS, Point A, prosthion, and forward and downward displacement at PNS (Table II), which suggested a counter-clockwise rotation of the maxilla. This was consistent with previous studies (16, 45, 46). The displacement patterns of Types B and C were more similar to each other than to Type A. This might be because the point of force application in Types B and C was the same (2 mm apical to the gingival crest of the alveolar bone between canines and premolar). Nevertheless, the difference in the displacement pattern between Types B and C on one hand, and Type A on the other hand might indicate a more inferior and anterior centre of rotation in Types B and C compared to Type A.

In the palatal plate model, the amount of forward displacement was larger than other models; however, undesirable counterclockwise rotation was found similar to other models. This might be because the points of force application in the models were inferior and posterior to the centre of rotation and the force direction was downward; however, the differences between the models depended on the difference in distance between these two points. Therefore, to minimize counter-clockwise rotation of the maxilla, changing the position of the hook to more forward or force vector to more downward might be recommended. Thus, further studies are warranted to investigate the effect of different force directions and points of force application as well as maxillary expansion on the application of the palatal plate in maxillary protraction.

The Von Mises stresses at the zygomaticomaxillary, zygomaticotemporal, zygomaticofrontal, and pterygomaxillary sutures were highest in Type A, which might suggest that orthopaedic force could...
be more effectively transferred to these sutures by the palatal plate than by other appliances. However, Type B showed the maximum stress value in the frontomaxillary suture. This might imply that in Types A and C, the orthopaedic forces were mainly transferred posteriorly, but in Type B, the forces were delivered upward to the midfacial area.

Overall, the stresses in the palatal plate model were distributed over the largest area compared to the other models. As Type C incorporated dental anchorage, stresses were concentrated on the anchorage teeth. Type B showed stress distributed over midfacial area including paranasal area. In Type A, there were light stresses on the first premolars due to the contact between the hook and the palatal alveolar margin of that tooth under the protraction force. It might be advisable to leave enough space between the hooks and the palatal slopes to avoid such an effect. Also, the simplicity of placing palatal plates makes them more efficient in comparison to other appliances.

Although these results provided information about the patterns of initial stress distribution and displacement in maxillary protraction with various appliances, the actual clinical situation might differ from these results because muscle, soft tissue, and growth were not considered in our study. In addition, a future study might be warranted to assess different components of stress. Moreover, the width of the midpalatal suture in our study was 0.5 mm, which was adopted from a porcine study (36). Therefore, the numerical values should be interpreted with caution.

For transverse maxillary deficiency, previous studies reported more anterior movement of the maxilla when protraction was combined with expansion compared to protraction without expansion (1, 33). Gautam et al. (45) reported that rotational tendency was not observed when 4 mm maxillary expansion was performed simultaneously. However, Vaughn et al. (47) found no significant difference in treatment effects between protraction with or without expansion in a randomized clinical trial. In our study, it would not be possible to simultaneously expand and protract the maxilla because the palatal plate might interfere with the opening of the midpalatal suture. Therefore, it is recommended to perform expansion prior to protraction when protraction with a palatal plate is considered.

In our study, the model of the palatal plate showed three hooks to which the elastics could be engaged to allow for changing the force vector according to the shape of the palate, relationship between upper and lower jaws and lips, face height, inclination of the occlusal plane, etc. However, in Type A, only the most coronal hook was engaged.

Yan et al. (29) compared the momentary effect of maxillary protraction with buccal plate versus conventional tooth-borne appliances using several force vectors. With a force vector direction of 30 degree, there was a clockwise rotation in the buccal plate model.
and a displacement in an almost no-rotation pattern in the dental anchorage model. However, in our study, both Types B and C showed counter-clockwise rotation in agreement with previous studies (45–51). The Von Mises stresses, in their study (29), were less in the buccal plate model than in the conventional one at the nasion and nosewing, but were greater at the zygomaticomaxillary, temporozygomatic, and pterygopalatine sutures. However, in our study, Type B showed greater stresses at the frontalmaxillary suture than those of Type C. Stresses at the pterygomaxillary and zygomatico-temporal sutures were similar in both types.

Clinically, the application of the palatal plate is easier than the buccal plate due to the flaps’ procedures and is more accurate due to the use of a jig (24). This results in less irritation to the soft tissues. The asymmetry in the palatal plate appliance shape has resulted in slight asymmetry in the results of our finite element analysis between right and left sides, especially on the transverse plane. However, this has no implications on the clinical situation as further movement will be restricted by the surrounding anatomical structures and the palatal plate appliance, which is fixed across the midpalatal suture. Also, the asymmetric design was made to avoid placing the miniscrews in the midpalatal suture that might interfere with palatal growth in adolescents (in the case of three miniscrews) or to avoid placing a fourth miniscrew as the three miniscrews were stable and sufficient for a successful treatment outcome. Therefore, the benefits of the asymmetric design outweigh the symmetric designs of the palatal plate.

As this finite element analysis is a momentary evaluation of the force application, further studies including creep strain and force application over time cycles are recommended to investigate the treatment effect of this appliance. Moreover, clinical assessment of the palatal plate appliance might be important to verify the results of this finite element analysis.

Conclusion

The maxillary protraction with a palatal plate was similar to that with a miniscrew placed at infrayzygomatic crest in producing forward displacement with counter-clockwise rotation. However, the palatal plate appliance showed larger amounts of forward displacement and wider distribution of stresses over the maxillofacial structures than with the buccally placed miniscrews and conventional appliances. It might be recommended to consider the application of the palatal plate for maxillary protraction in Class III patients.

Supplementary material

Supplementary material is available at European Journal of Orthodontics online.

References

5. Kokich, V.G., Shapiro, P.A., Oswald, R., Koskinen-Moffett, L. and Clare-


