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Stress distribution and displacement by different bone-borne palatal expanders with micro-implants: a three-dimensional finite-element analysis

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SUMMARY The aim of this study was to analyze stress distribution and displacement of the maxilla and teeth according to different designs of bone-borne palatal expanders using micro-implants. A three-dimensional (3D) finite-element (FE) model of the craniofacial bones and maxillary teeth was obtained. Four designs of rapid maxillary expanders: one with micro-implants placed lateral to mid-palatal suture (type 1), the second at the palatal slope (type 2), the third as in type 1 with additional conventional Hyrax arms (type 3), and the fourth surgically assisted tooth-borne expander (type 4) were added to the FE models. Expanders were activated transversely for 0.25 mm. Geometric nonlinear theory was applied to evaluate Von-Mises Stress distribution and displacement. All types exhibited downward displacement and demonstrated more horizontal movement in the posterior area. Type 3 showed the most transverse displacement. The rotational movement of dentoalveolar unit was larger in types 1 and 3, whereas it was relatively parallel in types 2 and 4. The stresses were concentrated around the micro-implants in types 1 and 3 only. Type 2 had the least stress concentrations around the anchorage and showed alveolar expansion without buccal inclination. It is recommended to apply temporary anchorage devices to the palatal slopes to support expanders for efficient treatment of maxillary transverse deficiency.

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Introduction

Rapid maxillary expansion (RME) is a well-established method to correct transverse maxillary deficiency and arch-length discrepancy. However, in adults, although nonsurgical palatal expansion might be possible, dentoalveolar tipping may cause detrimental periodontal effects such as bony dehiscence. Therefore, orthopedic expansion of the basal bone is crucial to avoid these effects and to establish proper posterior occlusion (Capelozza Filho *et al*., 1996; Chang *et al*., 1997; Garib *et al*., 2005; Koudstaal *et al*., 2009; Gurel *et al*., 2010; Baysal *et al*., 2011a).

Conventionally, surgically assisted RME has been applied to overcome the decreased elasticity of bone and increased resistance of interdigitated mid-palatal suture in adults (Kokich, 1976; Harzer *et al*., 2006; Tausche *et al*., 2007). Nevertheless, surgically assisted RME has resulted mainly in a lateral rotation of the two maxillary halves with only minimal horizontal translation and associated with large amount of relapse during postretention period (Byloff and Mossaz, 2004). Moreover, radiographic data has demonstrated some changes that might have a significant clinical impact on the periodontium (Gauthier *et al*., 2011).

Currently, temporary anchorage devices (TAD) have been applied to correct this transverse problem. Lee *et al*. (2010) reported a case with miniscrews in the paramedian area for a bone-borne RME connected to teeth. Also, Lagravere *et al*. (2010) have assessed the effect of bone-borne RME appliance with palatal slope anchor. The treatment effect of RME have been extensively studied through various methods including analysis of photoelastic models (Lima *et al*., 2011), laser holography (Pavlin and Vukicevic, 1984), and 3D finite-element (FE) models (Iseri *et al*., 1998; Jafari *et al*., 2003; Yu *et al*., 2007; Han *et al*., 2009; Lee *et al*., 2009; Boryor *et al*., 2010). The treatment effect of RME with TAD can be compared with other models in biomechanical variables such as displacements, strains, and stresses through the FE models. No study has evaluated the effects of bone-borne RME according to different anchorage sites.

The aim of this study was to analyze stress distribution and displacement of the maxilla and teeth according to different designs of RME using micro-implants on a 3D FE model of skull.

Materials and methods

Construction of an FE model

The FE model of the craniofacial bones and maxillary teeth was provided by Digimation Ltd (Lake Mary, FL, USA). This model was divided, the maxilla including the teeth and alveolar bone into 1 mm tetrahedrons and rest of the skull excluding the maxilla into 5 mm tetrahedrons. The difference in the maxillary elements between four types was because of different conditions caused by micro-implants, surgery, and expanders. The teeth, alveolar bone, and the periodontal ligament were considered to be homogenous and isotropic. Previously reported material properties of each component were shown in Table 1 (Staines *et al*., 1981; Tanne *et al*., 1987; Rees and Jacobsen, 1997; Mahoney *et al*., 2000).

The thickness of the cortical bone was modeled according to the study of Farnsworth *et al*. (2011); the thickness of the periodontal ligament was 0.2 mm (Kronfeld, 1931), and the mid-palatal suture was 0.5 mm (Fricke-Zech *et al*., 2012).

Table 1 Material properties.

	Young's moudulus (MPa)	Poisson's ratio
Diploe	1378	0.22
Table	10 204	0.30
Cortical bone	13 700	0.30
Cancellous bone	1370	0.30
PDL	50	0.49
Enamel	80 350	0.33
Dentin	19 890	0.31
Suture	10	0.49
Titanium	113 000	0.33
Resin	2000	0.30

Boundary condition and reference points

Foramen magnum was completely fixed and used as the origin point, as suggested by Gautam *et al*. (2007). The 3D co-ordinates were *X*, antero-posterior direction plane; *Y*, transverse direction; and *Z*, vertical direction. The mid-points of the buccal and lingual alveolar ridge of each tooth were used as reference points to evaluate alveolar bone displacement. Positive values indicate forward, outward, and upward displacements on the *X*, *Y*, and *Z* planes, respectively. The models were sectioned at canines and first molar by *YZ* plane and reference points were placed to assess teeth displacement (Figure 1).

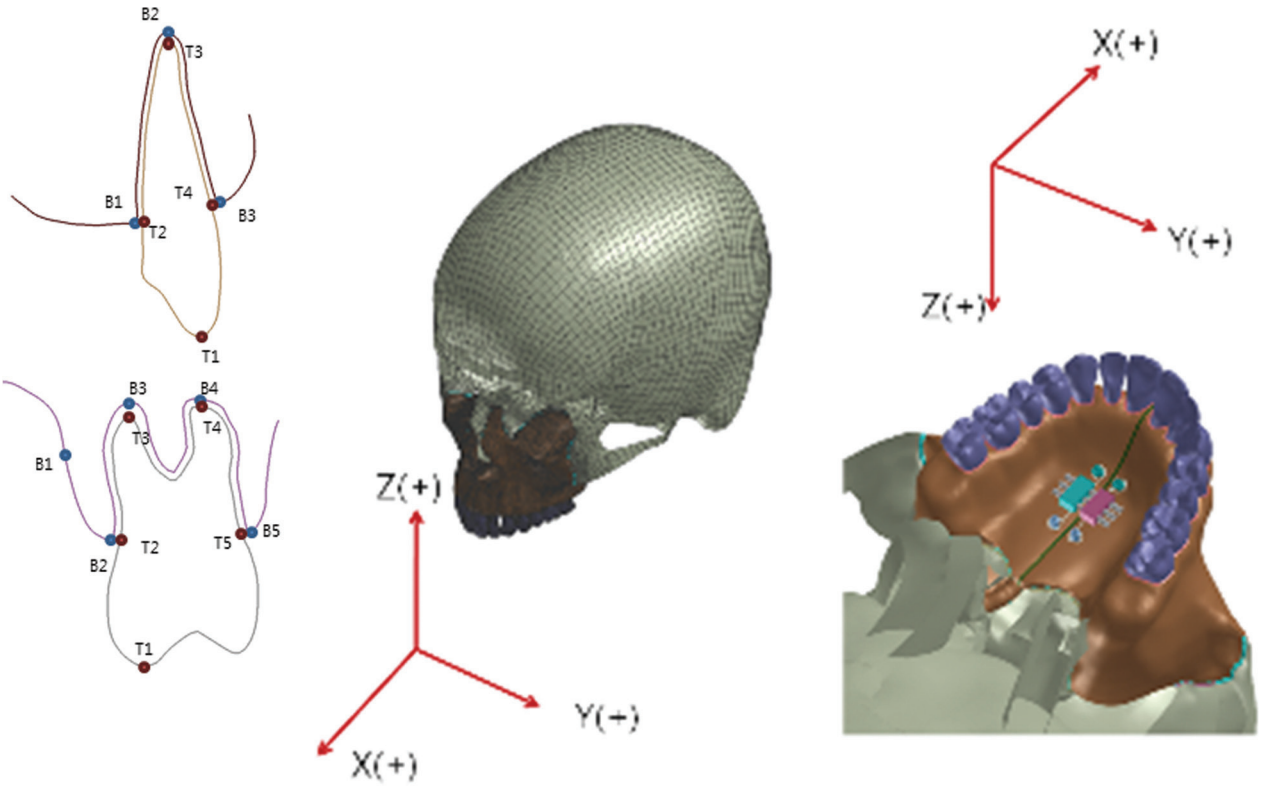

Figure 1 Schematic representation of the landmarks and 3D coordinates.

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Design of the appliance

In this study, expansion screw of 0.25 mm widening per turn and C-implant (C-implant co, Seoul, Korea) with 1.8 mm diameter and 8.5 mm length were used. Figure 2 shows four designs of expanders: three bone-borne expanders (types 1, 2, and 3) and one surgically assisted tooth-borne expander (type 4). In type 1, four C-implants were placed 3 mm lateral to mid-palatal suture and connected to the expander *via* 0.9-mm-diameter wires, which was not fixed into one unit to allow alteration. In type 2, four C-implants were placed 8 mm beneath the alveolar ridge at the palatal slope: two between the canines and first premolars and two between the second premolars and first molars. Then, the C-implants were connected to the expander through an acrylic resin cover. Type 3 was a conventional Hyrax type appliance connected to first premolars and first molars with the addition of four C-implants placed as in type 1. Type 4 was a conventional tooth-borne Hyrax type appliance assisted by surgeries at the mid-palatal suture, piriform aperture to maxillary tuberosity, and pterygomaxillary suture (Figure 3).

Expansion and analysis

Expanders were activated transversely for 0.25 mm in *Y* direction and were unfixed in *X* and *Z* directions to prevent interference with the resultant movement.

For FE analysis, the following software programs were used: Visual-mesh V 7.0 for meshing, PAM-MEDYSA V 2011 for solving, and Visual-Viewer 7.0 for postprocessing (ESI Group, France). Geometric nonlinear theory and implicit method were applied for analysis. Von-Mises Stress distribution and the dental and alveolar bone displacement were evaluated.

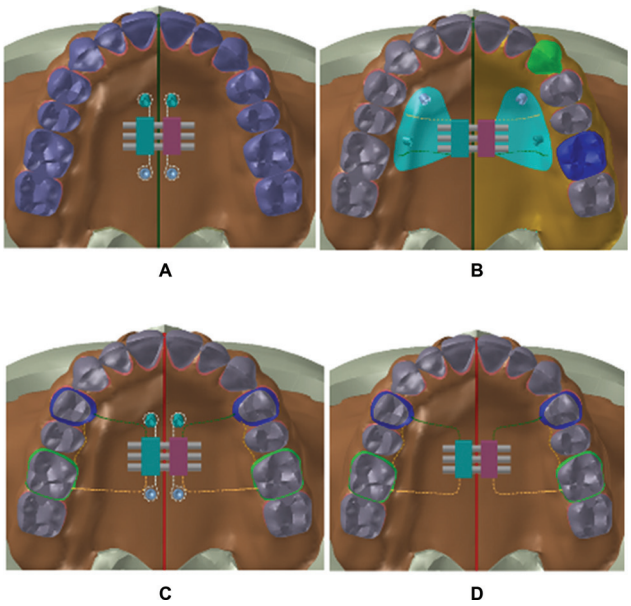

Figure 2 Designs of the RME types: (A) bone-borne expander with micro-implants placed 3 mm lateral to mid-palatal suture (type 1); (B) bone-borne expander with micro-implants placed at the palatal slope (type 2); (C) combined expander with additional conventional Hyrax arms on the first premolar and first molar (type 3); (D) surgically assisted tooth-borne expander (type 4).

Results

Stress distribution

Type 1 showed that stress was concentrated around the micro-implants and the mid-palatal suture with a maximum value of 0.362 GPa. No stresses were observed around the roots. Weaker stresses were distributed through the lingual alveolar bone of the first premolar in cross section.

On the other hand, type 2 demonstrated low stresses distributed evenly around the micro-implants. The cross-sectional view of the first premolar area showed the least amount of stress around the roots. Stresses concentrated in the mid-palatal suture were less than those in type 1 with a maximum value of 0.046 GPa.

Type 3 had large amount of stresses located in the mid-palatal suture and around micro-implants and roots of the anchor teeth. Maximum stress concentration (0.368 GPa) was shown around the roots of the first premolar in the cross section.

Also, in type 4, high stresses were concentrated around the anchor teeth with a maximum value of 0.016 GPa and

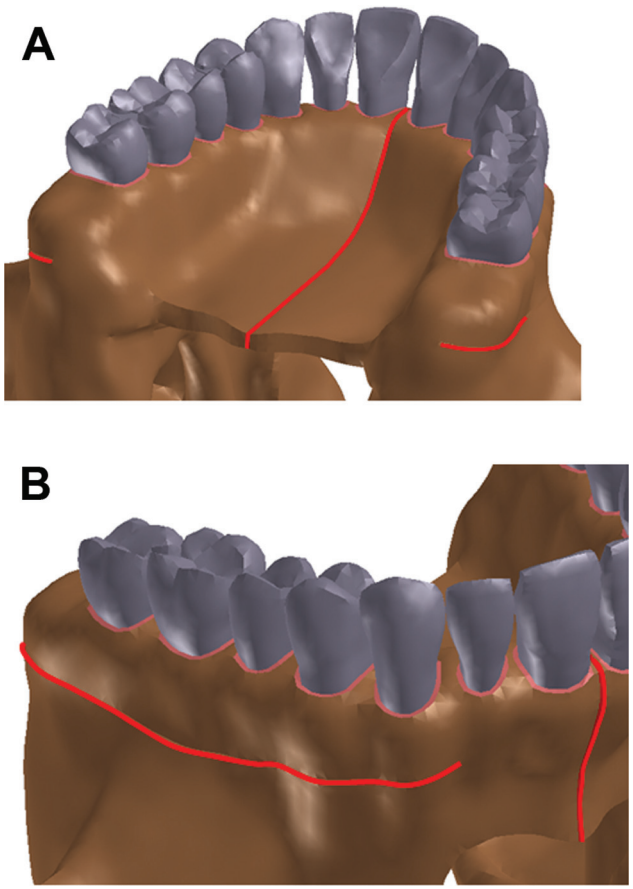

Figure 3 Graphical representation of the cut lines of the surgery on type 4 model. (A) palatal view; (B) buccal view.

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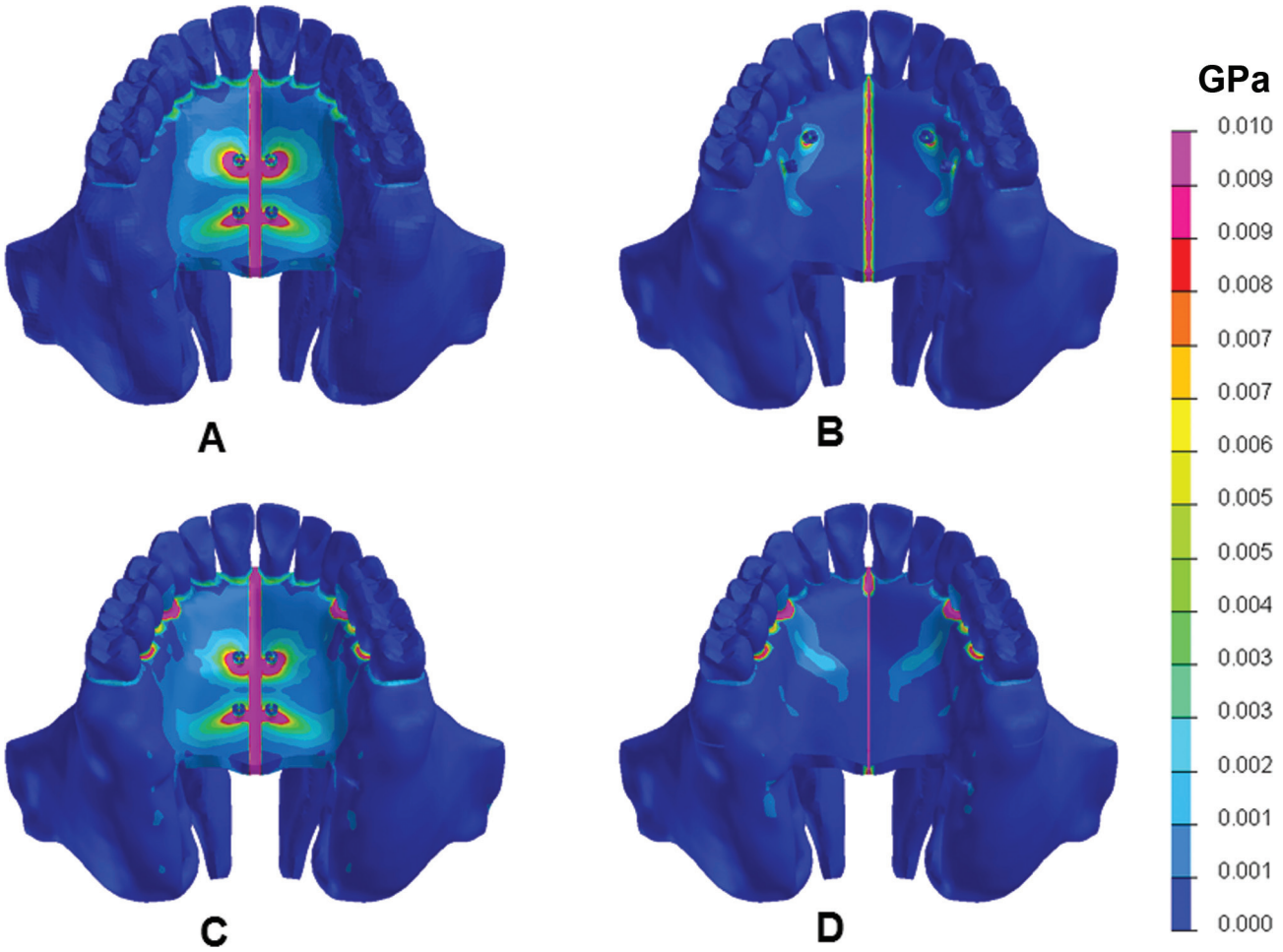

Figure 4 Von-Mises stress distribution in occlusal view. (A) Type 1; (B) type 2; (C) type 3; (D) type 4.

smaller amounts on the palatal slope. The cross-sectional view showed concentrations of stresses around the roots and alveolar bone. However, weak stresses were located in the mid-palatal suture. (Figures 4 and 5)

Displacement of the alveolar bone

Tables 2 and 3 represent the amount of 3D displacement of the alveolar bone reference points at the canine and first molar, respectively.

Types 1 and 2 showed backward displacement on the *X* axis. In types 3 and 4, forward displacement of the alveolar bone was noticed, particularly in the premolar and the first molar areas (Figure 6).

In all types, the outward displacement on the *Y* axis of the posterior area was greater than anterior. However, types 3 and 4 showed increased amount of displacement at the first premolar area (Figure 7).

The lingual alveolar bone showed inferior displacement on the *Z* axis in all types. In the buccal alveolar bone, it was inferior in the anteriors, but superior in the posterior area in types 1 and 2. However, in types 3 and 4, inferior displacement occurred in whole alveolar bone (Figure 8). The total displacement was larger in types 3 and 4 lingually and buccally, whereas type 2 showed the least total displacement for all teeth (Figure 9).

The rotation of the line connecting the buccal and lingual alveolar crests at the first molar area (B2-B5) were larger in types 1 and 3 (0.91°) compared with types 2 and 4 (0.68° and 0.15°, respectively) which revealed a relatively parallel movement.

Teeth displacement

Tables 2 and 3 represent the amount of 3D displacement of the dental reference points at the canine and first molar, respectively.

In type 1, since the frontomaxillary suture was the center of rotation, palatal halves were displaced transversely with more expansion of the inferior part. The displacement of teeth followed the buccal rotational movement of the

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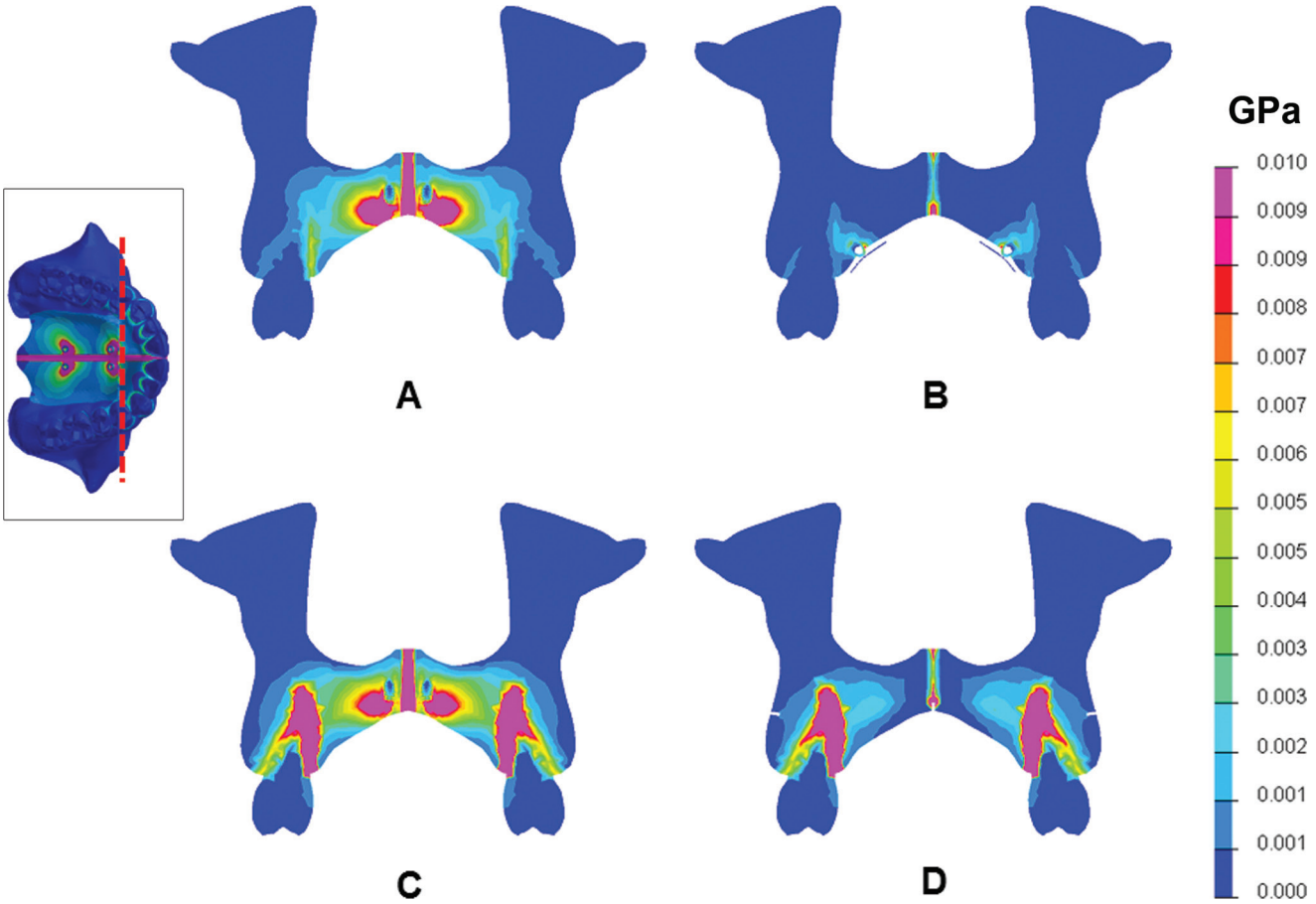

Figure 5 Von-Mises stress distribution in cross-section at the first premolar area. (A) type 1; (B) type 2; (C) type 3; (D) type 4.

alveolar bone. However, type 2 showed parallel separation of the mid-palatal suture.

Type 3 showed more buccal rotation of the dentition in addition to the buccal rotational movement of the alveolar bone. In type 4, the displacement of teeth occurred first, then the transformation of the periodontal ligament, and small amount of deformation of the alveolar bone. The change in the alveolar bone was less than that in type 3. It showed small alteration in the *Y* axis and large change in *X* axis (Figure 10).

Discussion

The predictability of orthopedic expansion is greatly reduced after 15 years of age (Melsen, 1975; Baccetti *et al*.,

Table 2 Displacement of the canine reference points under loading in each type in the antero-posterior (*X*), transverse (*Y*), and vertical (*Z*) directions.

Reference points	Type 1			Type 2			Type 3			Type 4		
	X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
B1 (Lingual alveolar crest)	−0.279	0.395	−0.601	−0.486	0.058	−0.073	−0.067	0.473	−0.684	0.560	0.168	−0.168
B2 (Socket)	−0.165	0.304	−0.162	−0.246	0.051	−0.030	0.213	0.382	−0.342	0.700	0.136	−0.186
B3 (Buccal alveolar crest)	−0.139	0.294	−0.030	−0.191	0.052	−0.006	0.270	0.335	−0.137	0.708	0.075	−0.061
T1 (Cusp tip)	−0.247	0.504	−0.043	−0.181	0.219	0.043	0.173	0.631	−0.305	0.689	0.165	−0.333
T2 (Lingual CEJ)	−0.235	0.245	−0.265	−0.270	0.036	−0.040	0.142	0.302	−0.406	0.699	0.117	−0.162
T3 (Root apex)	−0.097	0.391	−0.159	−0.277	0.054	−0.027	0.315	0.503	−0.262	0.764	0.191	−0.110
T4 (Buccal CEJ)	0.072	0.768	−0.128	−0.389	0.101	−0.024	0.514	1.020	−0.223	0.856	0.394	−0.092

Unit = mm; CEJ = cementoenamel junction; origin point = foramen magnum.

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Table 3 Displacement of the first molar reference points under loading in each type in the antero-posterior (*X*), transverse (*Y*) and vertical (*Z*) directions.

Reference points	Type 1			Type 2			Type 3			Type 4		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
B1 (Lingual mid-alveolar bone)	−0.311	0.565	−0.174	−0.191	0.260	−0.055	0.169	0.751	−0.375	0.766	0.230	−0.293
B2 (Lingual alveolar crest)	−0.311	0.601	−0.131	−0.233	0.303	−0.037	0.227	0.853	−0.308	0.829	0.301	−0.259
B3 (Lingual socket)	−0.284	0.475	−0.076	−0.185	0.186	0.018	0.149	0.593	−0.299	0.693	0.150	−0.302
B4 (Mesiobuccal socket)	−0.236	0.428	−0.003	−0.173	0.169	0.061	0.170	0.529	−0.198	0.654	0.125	−0.259
B5 (Buccal alveolar crest)	−0.220	0.543	0.040	−0.180	0.254	0.085	0.232	0.739	−0.113	0.729	0.238	−0.211
T1 (Mesiolingual cusp tip)	−0.254	0.713	−0.034	−0.212	0.395	0.049	0.578	1.232	−0.317	1.131	0.583	−0.348
T2 (Lingual CEJ)	−0.325	0.696	−0.131	−0.244	0.380	−0.034	0.471	1.177	−0.653	1.081	0.543	−0.595
T3 (Lingual root apex)	−0.299	0.564	−0.116	−0.212	0.267	−0.021	0.179	0.774	−0.522	0.757	0.256	−0.479
T4 (Mesiobuccal root apex)	−0.255	0.545	−0.061	−0.190	0.251	0.027	0.188	0.716	−0.372	0.723	0.215	−0.381
T5 (Buccal CEJ)	−0.073	0.663	−0.275	−0.407	0.088	−0.040	0.317	0.877	−0.421	0.782	0.338	−0.171

Unit = mm; CEJ = cementoenamel junction; origin point = foramen magnum.

2001). The stability of the treatment outcome of the RME with or without surgical assistance was dubious (Alpern and Yurosko, 1987; Cross and McDonald, 2000; Lagravère *et al*., 2006; Baysal *et al*., 2011b). Consequently, bone-borne expanders with TADs can be a viable treatment option. Since the forces can be directly applied to the basal bone, the amount of skeletal effect of treatment may increase. Thus, the purpose of this study was to compare treatment effect of different designs of bone-borne appliances using micro-implants.

Recent articles about treatment effects of these bone-borne expanders demonstrated contradictory results. A case report applied a combined design incorporating miniscrews placed in the paramedian area with bands on teeth as an anchorage for RME and showed a successful treatment outcome (Lee *et al*., 2010). This design was similar to type 3 in our study. Another study has applied skeletal anchorage to the palatal slopes, which is similar to type 2. It showed no significant differences between this design and the tooth-borne RME (Lagravere *et al*., 2010). However, type 2 was the most efficient expander in our study. In agreement with our results, the outcome of the treatment in both reports showed that the expansion in the posterior area was more than that in the anterior region (Lee *et al*., 2010; Lagravere *et al*., 2010).

Tooth-borne RME showed controversial treatment results regarding the amount of maxillary transverse expansion antroposteriorly. Akkaya *et al*. (1998) and Wertz (1970) reported that transverse expansion was larger in the anterior part, whereas Davidovitch *et al*. (2005) stated that parallel expansion occurred. On the other hand, Lagravère *et al*. (2006) concluded that more expansion on the posterior part was achieved by surgically assisted expansion.

Previous studies showed that the mid-palatal and pterygomaxillary sutures are the primary anatomic resistance to expansion (Chaconas and Caputo, 1982). This agrees with the high-stress concentrations in the mid-palatal suture in our FE model. Interestingly, Nonparallel displacement of the maxillary halves was reported with the wider opening to the anterior (Lee *et al*., 2009). However, in our study, transverse expansion in all types occurred largely in the posterior area. This was because the mid-palatal suture area of the finite model was filled with cortical and cancellous bone adopting the properties of the mid-palatal suture stated by Yu *et al*. (2007). Moreover, the load was directly applied to the posterior palate that has thinner cortical bone than the anterior area. Although the Young's modulus of the mid-palatal suture was smaller than that of the bone, the force needed to separate it was large enough to bend the expander's wire.

In type 1, the alveolar bone rotated buccally, whereas in type 2 parallel displacement occurred and low stress was distributed on the mid-palatal area. Of all types, type 2 seemed to be the most efficient bone-anchored maxillary expander because the stress was distributed widely throughout the palate, decreasing the stress around the micro-implant and resulting in dentoalveolar expansion without buccal inclination of the dentition. Therefore, it would be advisable to apply bone-anchored device in adults instead of the tooth-borne expanders.

The largest transverse displacement in the dentoalveolar unit was in type 3 followed by 1, 4, and then 2. However, in type 2, alveolar expansion was achieved without buccal inclination of the dentition because the expander was not connected to teeth. On the other hand, type 3 showed buccal inclination.

In type 4, the bone resistance area was surgically cut. Therefore, the minimal stresses were located on the mid-palatal suture area, whereas high concentrations were on the alveolar bone around the anchorage teeth. In addition, the change in angle between the line connecting the palatal and buccal alveolar crests (B2–B5) before and after the

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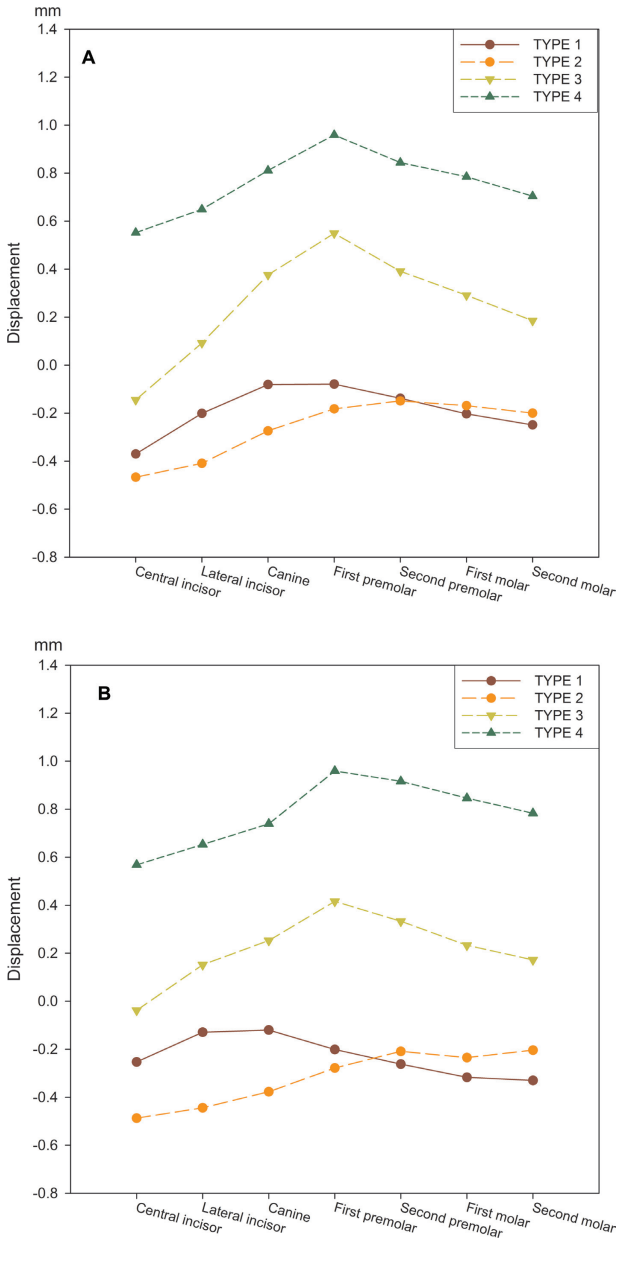

Figure 6 *X*-displacement of the alveolar bone of each tooth in types 1–4. (A) buccal; (B) lingual.

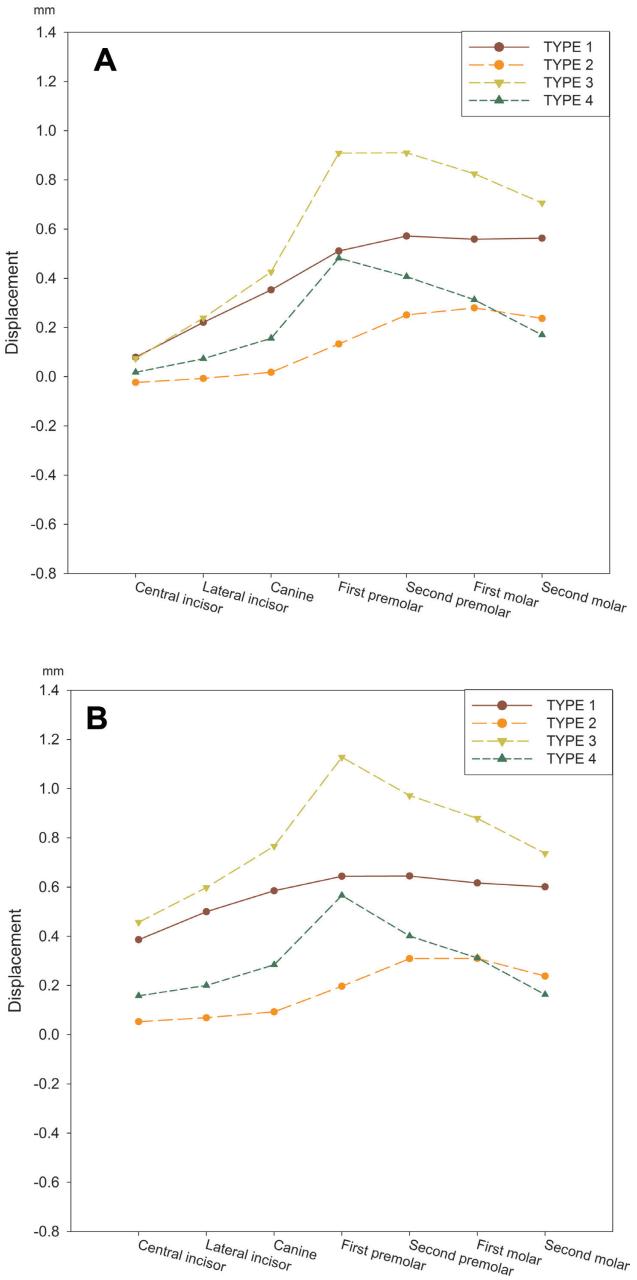

Figure 7 *Y*-displacement of the alveolar bone of each tooth in types 1–4. (A) buccal; (B) lingual.

application of force was minimal in type 4 compared with other types. This suggests more parallel movement of the dentoalveolar unit in type 4.

A previous study showed that the central incisors moved downward and backward in both solid and fused-suture models but moved primarily downward in the patent-suture model (Lee *et al*., 2009). However, extrusion movement was reported in surgically assisted rapid maxillary expansion under different surgical conditions (Han *et al*., 2009). Also, a clinical study noted downward and forward displacement of the maxilla during expansion (Doruk *et al*., 2004). In our study, all types showed extrusive displacement of the dentoalveolar unit, except the posterior buccal bone of types 1 and 2. In particular, types 1 and 3 showed more extrusive movement in the anterior part, whereas in type 4 it was more posteriorly. This might be due to the design of the surgery, which decreases the resistance at the posterior area from all directions including mid-palatal suture, piriform aperture to tuberosity, and pterygomaxillary suture.

Also, the transverse displacement in their study was mainly in the posterior area. In the antero-posterior direction, the anterior teeth moved lingually except with

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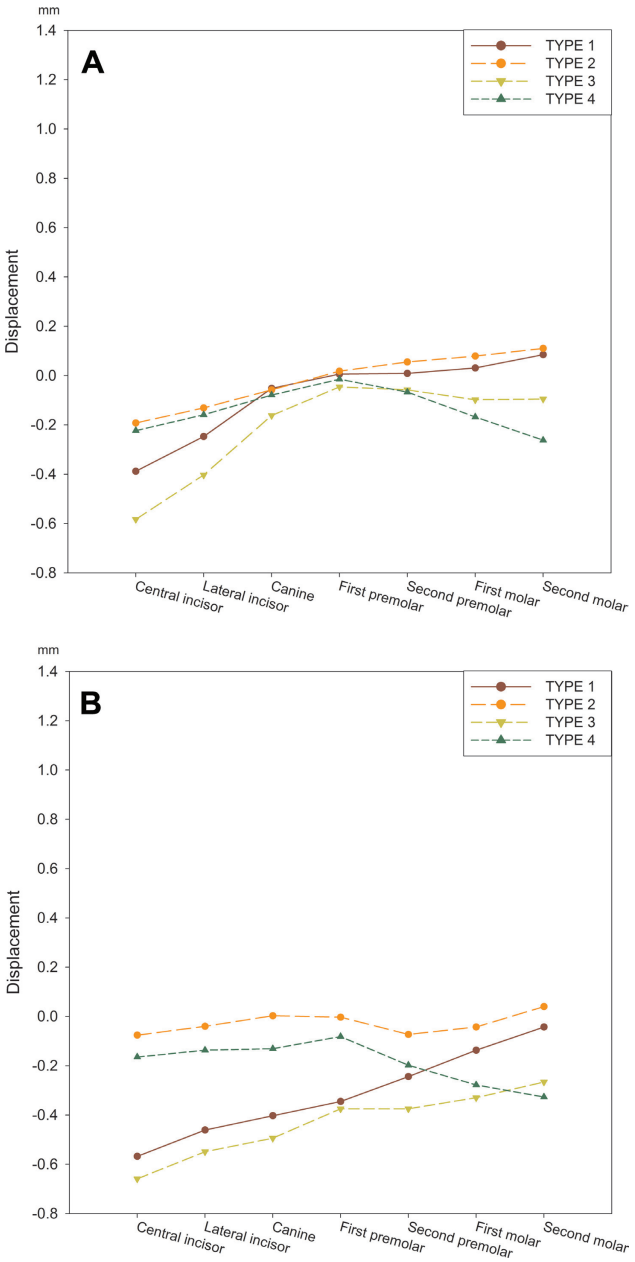

Figure 8 *Z*-displacement of the alveolar bone of each tooth in types 1–4. (A) buccal; (B) lingual.

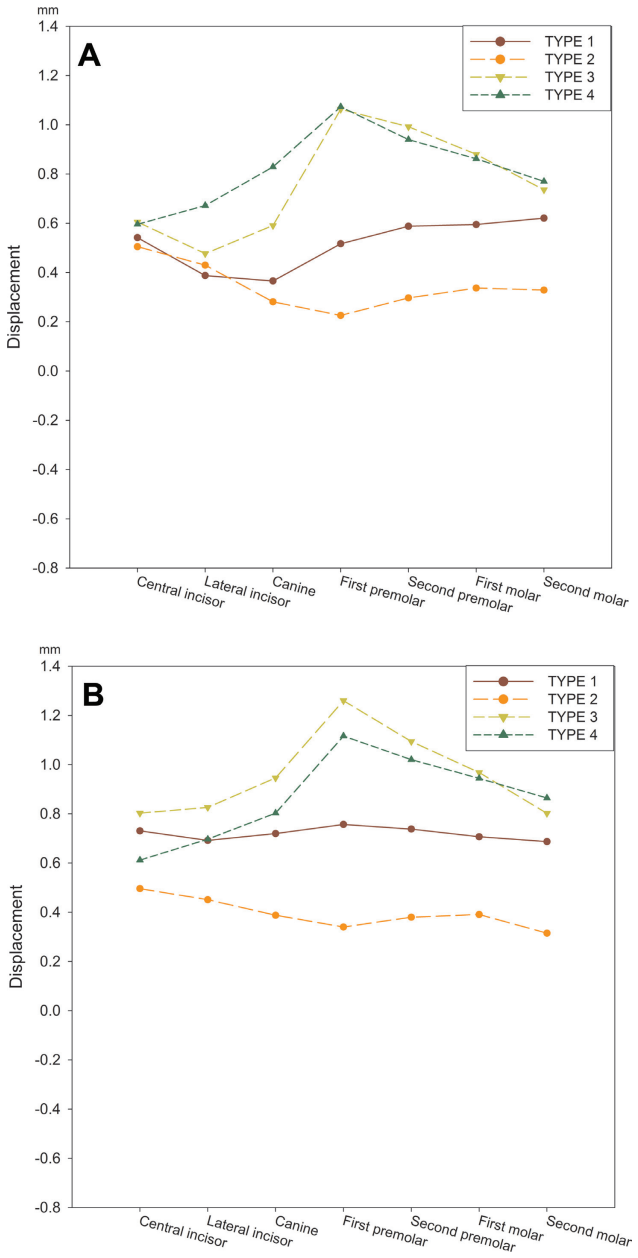

Figure 9 Total displacement of the alveolar bone of each tooth in types 1–4. (A) buccal; (B) lingual.

complicated surgical procedures including Le Fort I, paramedian osteotomy, and pterygomaxillary separation (Han *et al*., 2009). However, in our study, the displacement occurred anteriorly in types 3 and 4, and posteriorly in types 1 and 2. This might be because types 3 and 4 included the first premolar and molar in their design, whereas types 1 and 2 were completely bone-borne. This inconsistency between the studies might be due to the difference in the model construction, as their model lacked the mid-palatal suture. Also, the different design of the expanders might have played a role.

Nevertheless, this study was a mathematical modeling based on a dry skull, which might decrease the resemblance to the clinical situation. Also, in such models, although the hexahedron is more accurate than the tetrahedron, it produces a complicated design of the micro-implants. Therefore, in our study, tetrahedron was applied in modeling instead. In addition, the 3D FE analysis evaluated the initial stress distribution and displacement patterns. Moreover, our study has evaluated the stresses in the maxilla only. Therefore, a future study is recommended to assess the effect of the RME on the whole craniofacial structure and to include diverse

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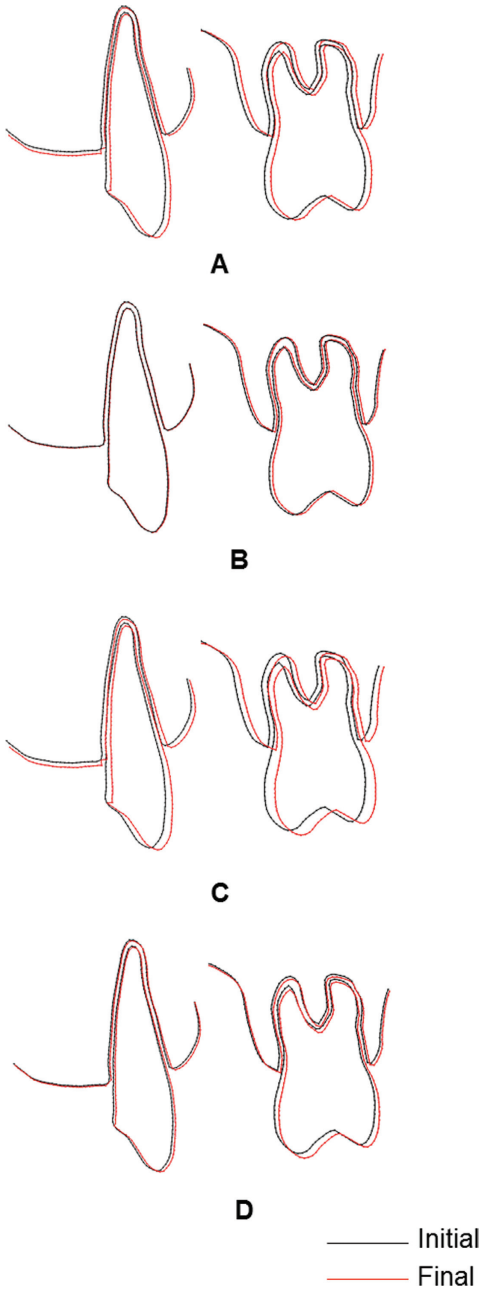

Figure 10 Superimposition of initial and final sectioned models at canine and first molar: Magnifications ×50; reference point: Foramen magnum.
(A) Type 1; (B) type 2; (C) type 3; (D) type 4.

surgically assisted RME techniques with the implementation of the time factor to evaluate sequential expansion and to model viscoelastic and recovery material effects.

Conclusion

Within the limits of this study, the 3D FE analysis of maxillary expansion using three types of bone-borne expanders with micro-implants and one surgically assisted expander showed the following:

- All types exhibited downward displacement and demonstrated more horizontal movement in the posterior area. Anterior displacement occurred in types 3 and 4, whereas posterior displacement was in types 1 and 2.
- Type 2 had the least stress concentrations around the anchorage and showed alveolar expansion without buccal inclination of the dentition.

Therefore, it is recommended to apply temporary anchorage devices to the palatal slopes to support expanders for efficient treatment of maxillary transverse deficiency.

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