Biomechanical study of midpalatine suture and miniscrews affected by maturation of midpalatine suture, monocortical and bicortical miniscrew placement in bone-borne rapid palatal expander: a finite element study

Chayapa Sermboonsang[1], Nattapon Chantarapanich[2*], Samroeng Inglam[1] and Kanlaya Insee[3]

[1]*Faculty of Dentistry, Thammasat University, Pathumthani 12120, Thailand*
[2]*Department of Mechanical Engineering, Faculty of Engineering at Sriracha, Kasetsart University Sriracha Campus, Chonburi, 20230 Thailand*
[3]*Department of Orthodontics, Faculty of Dentistry, Thammasat University, Pathumthani 12120, Thailand*
[*]*Corresponding author: nattapon@eng.src.ku.ac.th*

Received: January 12, 2020; Revised: May 16, 2020; Accepted: May 22, 2020

ABSTRACT

This study aimed to investigate the biomechanical performance of different miniscrews placement techniques in different stages of midpalatine suture maturation using finite element analysis. Four models of partial nasomaxillary structure with bone-borne rapid palatal expander were constructed with monocortical and bicortical placement types with partly ossified midpalatine suture and completed ossified midpalatine suture. From the finding, both monocortical and bicortical techniques is able to separate partly ossified suture. The separation of completed ossified midpalatine was even more difficult than partly ossified suture because the separation was not clearly observed and higher stress exhibited on expander. However, the bicortical placement technique was observed to be more parallel pattern of suture expansion. In all Finite Element (FE) cases, von Mises stress exhibited on neck and upper intraosseous part of miniscrew in monocortical model. In midpalatine suture, the bicortical model can produce high stress in superior and inferior region of midpalatine suture, whereas monocortical can diffuse only inferior of suture. The completed ossified midpalatine suture shows low stress level along the suture and has insignificant displacement. The elastic strain pattern at peri-implant site in monocortical model was high at medial tip and lateral at cortical margin. For bicortical model, the elastic strain concentrated at upper intraosseous. The bicortical placement technique has more advantages in promote parallel maxillary bone expansion, decrease deformation risk and increase stability of appliance.

Keywords: maxillary expansion; bone-borne rapid palatal expander; midpalatine suture

1. INTRODUCTION

Maxillary transverse deficiency is a definition of disproportion between the width of the upper and lower dental arches, clinically represented as crowding of maxillary teeth, complete unilateral or bilateral cross bite and dental inclination compensation in the upper or lower posterior teeth or combination. Furthermore, malocclusion and aesthetic problems from this abnormality may lead to functional impairments such as low masticatory ability index (MAI) and food intake ability (FIA) (Choi et al., 2015). The etiology can be abnormal oral habits such as thumb sucking and mouth

ISSN Online 2630-0087

breathing habits or skeletal structure discrepancy or even dysfunction from muscle disorders and congenital syndromes. The prevalence of maxillary transverse deficiency was 11.72% in mixed dentition and 9.39% in permanent dentition (Alhammadi et al., 2018) and, incidence of the transverse maxillomandibular discrepancy is between 8% and 18% among adult patients with an orthodontic malocclusion (Corega et al., 2010).

In conventional treatment of maxillary transverse deficiency, patients should be treated with maxillary expansion while still growing. Early treatment is subsequently to deliver the better the prognosis and the outcomes (Baccetti et al., 2001). When patient growth, midpalatal suture calcifies and interdigitates which becomes more difficult in treatment. This is because, the increase of mechanical resistance in suture during expansion. Thus, maxillary expansion treatment relates to patient age and skeletal maturation (Persson and Thilander, 1977). Many studies were found that at the age of teenager tends to have greater buccal tip inclination of anchor teeth, buccal bone dehiscence and less bone expansion than younger age (Baysal et al., 2013; Baccetti et al., 2001, Erverdi et al., 1994).

The expander without anchor implant was a first technique to manage the maxillary transverse deficiency by anchor at teeth. This technique was unsuccessful in late growth patient, because the expansion force concentrated at teeth and subsequently lead to buccal tipping with less any suture expansion. Therefore, another technique to overcome disadvantage of the conventional technique is surgically-assisted rapid palatal expansion (SARPE). This treatment consistes surgical procedure to split maxillary into half and combined with expander appliance. This procedure increases success rate, and reduces dental side effects (Northway and Meade, 1997). Nevertheless, it still requires hospitalization, general anesthesia, and high cost procedure.

The better alternative technique, which can reduce the risk of patient, is to use the devices called bone-borne rapid palatal expander (B-RPE). This device is designed to have the anchored structure directly to bone layer without involvement to teeth. The anchored structure is miniscrew, which has diameter ranges between 1.5 and 2.0 mm (Mosleh et al. 2015; Winsauer et al., 2013; Kim and Helmkamp, 2012). The force from expander transfers to these miniscrew to break the increased maturation midpalatal suture and displace the maxillary structure more than buccal tipping teeth (Mosleh et al., 2015; Winsauer et al., 2013), which the others devices cannot achieve.

However, the application of miniscrews with expanders has just been prevail. The factors associated to failure or success of treatment have still not been much paid attention. In addition, during clinical work, patients may have various anatomical factors such as, bone height level, vary midpalatine suture maturation stage, and especially a miniscrew placement technique.

For the miniscrew placement technique, only the study of Lee et al. (2017) concentrated on this issue where most study (Seong et al., 2018; Carvalho Trojan et al., 2017; Lee et al., 2014) concentrated device configurations. For miniscrew placement technique, this study focused on monocoritcal and bicortical placement. This issue is still lack of evidence to point out the better technique.

2. MATERIALS AND METHODS

2.1 Materials

All bone models was derived from nasomaxillary region. Bone, expander device, and appliance set was created using Computer Aided Design (CAD) software (VISI, Vero Software, UK). The computational analysis was performed using Finite Element (FE) software (MSC Marc Mentat, MSC Software, USA). The expander appliance used in this study was Hyrax® (Dentaurum, Germany), made of stainless steel. Miniscrew was Bio-Ray (Syntec Scientific Corp., Taipei, Taiwan).

2.2 Nasomaxillary and expander device 3D models

Plastic skull was scanned with Cone Beam Computer Tomography (CBCT) scanner. The images from the scanning was used in 3D model reconstruction using Dolphin 3D imaging software (Patterson Dental Supply, USA). During reconstruction process, only the nasomaxillary region was selected and extracted. In addition, mandible model was removed to produce the 3D model of nasomaxillary. The 3D model of nasomaxillary complex was modified cortical thickness to achieve between 1.2 and 2.0 mm (Farnsworth et al., 2011) using CAD. In addition, the 3D model was identified the midpalatine suture which present the half of right and left side. The midpalatine suture was 1.5-2.0 mm in width. (MacGinnis et al., 2014; Soboleski et al., 1997) Both sides were symmetric by replicating the other half using mirror simulation.

The expander set included expander appliance and four miniscrews. Its specification included maximum expansion of 10 mm, full turn expansion length of 0.8 mm. The miniscrew was 2 mm in diameter and lengths of 14 mm for bicortical placement and 8 mm for monocortical engagements. The 3D model of expander set was created from CAD software.

The expander and the miniscrews were aligned to nasomaxillary bone on palate, the miniscrew were placed 3 mm lateral to midpalatine suture and connected to the expander via 1.4 mm diameter wires. Two of the miniscrews were placed between the first premolar and second premolar another 2 were placed between first molar and second molar regions.

The studied models had four cases with different midpalatine suture properties and miniscrew placement type, as shown in Table 1. All analysis cases were performed using FE method.

Table 1 Cases in study

Case No.	Midpalatine suture properties	Miniscrew placement
1	Partial ossified	Monocortical
2	Complete ossified	Monocortical
3	Partial ossified	Bicortical
4	Complete ossified	Bicortical

2.3 Element generation

Elements of all 3D models were generated from element generating program. Four nodes tetrahedral element was used to build up the FE models. Four different numbers of element were generated to perform convergence tests for mono-cortical and bi-cortical FE models. Minimum number of element of FE result that are not affected by changing the number of element for each case was selected to use in this study. In this case, von Mises stress exhibited on expander and screw was used to monitor.

2.4 Material properties

The material properties used are shown in Table 2. At the midpalatine suture region, it was incorporated with different materials properties for each case study to simulate maturation stage as partial ossified stage D and completed ossified suture stage E according to Angelieri et al. (2013)

A partly ossified suture case was simulated by assigning unossified suture properties at maxilla midpalatine suture, but remain midpalatine suture at palatine bone as surrounding bone properties. For completed ossified suture, the maxilla and palatine midpalatine suture was incorporated with cortical bone and cancellous properties. All other cranial sutures were fused and assigned with properties of bone. Each material was considered to be homogeneous, isotropic, and linearly elastic

Table 2 Materials properties (Lee et al., 2017; Ludwig et al., 2013; Provatidis et al., 2008; Lee et al., 2009)

Materials	Elastic modulus (MPa)	Possion's ratio
Cortical bone	13,700	0.30
Cancellous bone	1,370	0.30
Unossified suture	0.667	0.49
Stainless steel	210,000	0.30

2.5 Boundary condition

Boundary condition of the FE model included all constrained displacements at superior of partial zygomatic, sphenoid and temporal bone of left and right side. The load acting on expander was determined as displacement of expander which at 0.2 mm each side, which resulted in activated gap opening of 0.4 mm in the transverse plane. All boundary condition 8 are presented in Figure 1.

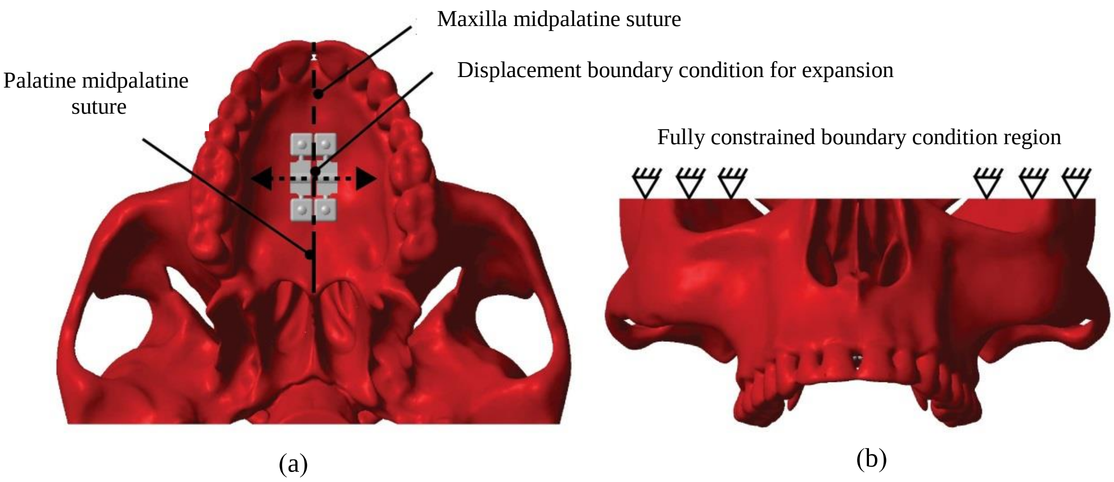

Figure 1 3D model of partial nasomaxillary structure with B-RPE and boundary condition for FE analysis; (a) occlusal view of 3D model and displacement boundary condition of expander 0.2 mm each side, total expansion 0.4 mm, (b) frontal view of 3D model and fully constrained boundary condition at partial zygomatic, sphenoid and temporal bone of left and right side

2.6 Contact condition

All bone structures were set as no relative displacement. Partial relative displacement properties at midpalatine suture within maxilla bone area in partly ossified suture model whereas mid-palatine suture at palatine bone was still connected. The expander and miniscrew was also no relative displacement. Miniscrew-bone contact was assumed fully anchor.

3. RESULTS

3.1 Convergence test

The result of von Mises stress exhibited on screw and expander from each employed number of element, as shown in Figure 2. According to the test, the number of element are 828,492 elements with 211,838 nodes in monobicortical model, whereas 686,248 elements with 176,962 nodes in bicortical model.

3.2 Transverse displacement at suture

There are no displacement shown in completed ossified cases (No. 2 and No. 4). Only partial ossified cases which present the transverse displacement along the suture line where maximum displacement was found at inferoanterior region of palate. Values of displacement were collected along suture line, which are shown in Figure 3 and 4.

3.3 Von Mises stress

The von Mises stress on miniscrew were located on the neck, and upper portion of intraosseus length. Case No. 2 presented the higher von Mises stress values, which reached 8,228.13 MPa. The values in monocortical cases were more than bicortical cases. For all expander models, stress concentrated at connecting wire.

Figure 5 shows the stress distribution of screw and expander, the values shown in Table 3. The high stress located at inferoanterior midpalatine suture at palatine region in monocortical case No. 1 whereas the high stress located at superoanterior and inferoanterior regions in bicortical bone case No. 3. All stress concentration sites and values are shown in Figure 6 and Table 4.

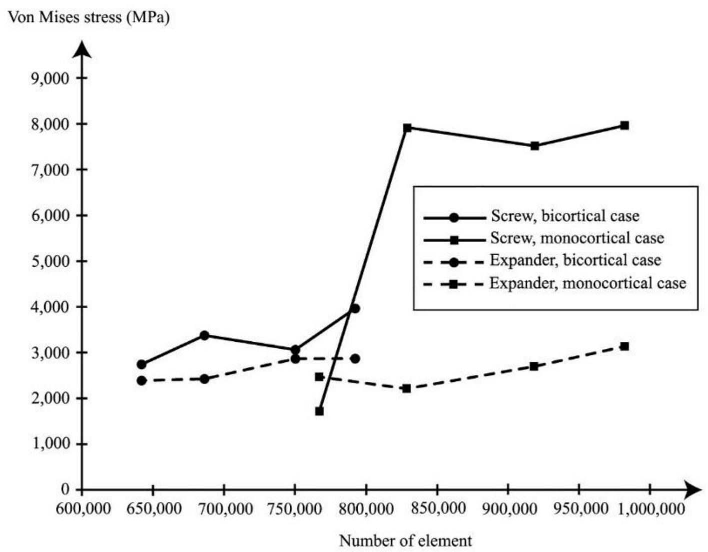

Figure 2 Convergence test

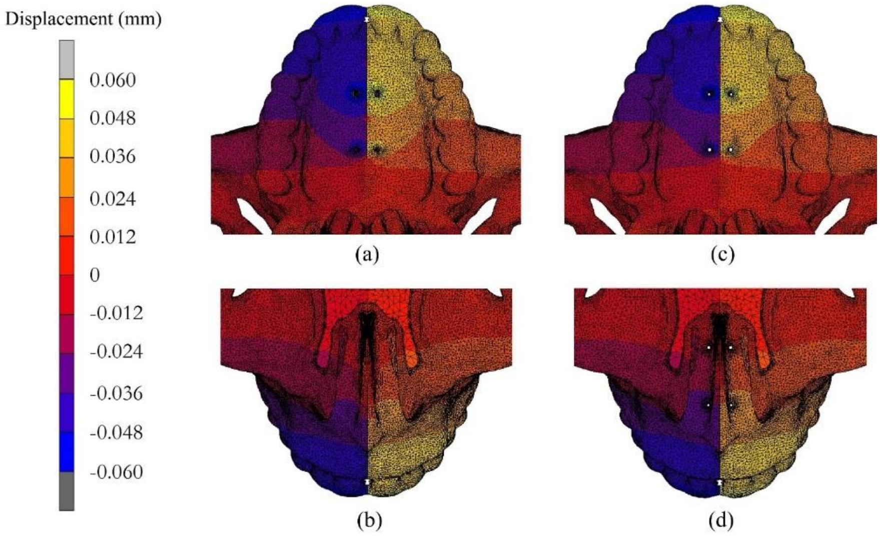

Figure 3 The displacement in partly ossified midpalatine suture case; (a) occlusal view of case No. 1, (b) superior view of case No. 1, (c) occlusal view of case No. 3, (d) superior view of case No. 3

Table 3 Maximum von Mises stress on appliance

Case No.	Maximum von Mises stress on miniscrew (MPa)	Maximum von Mises stress on expander (MPa)
1	7,922.06	2,209.23
2	8,228.13	2,434.43
3	3,375.50	2,424.67
4	4,273.78	2,638.09

Table 4 Von Mises stress on midpalatine suture at palatine bone

Case No.	Von Mises stress at inferoanterior area (MPa)	Von Mises stress at superoanterior area (MPa)
1	71.00	8.05
3	51.78	79.93

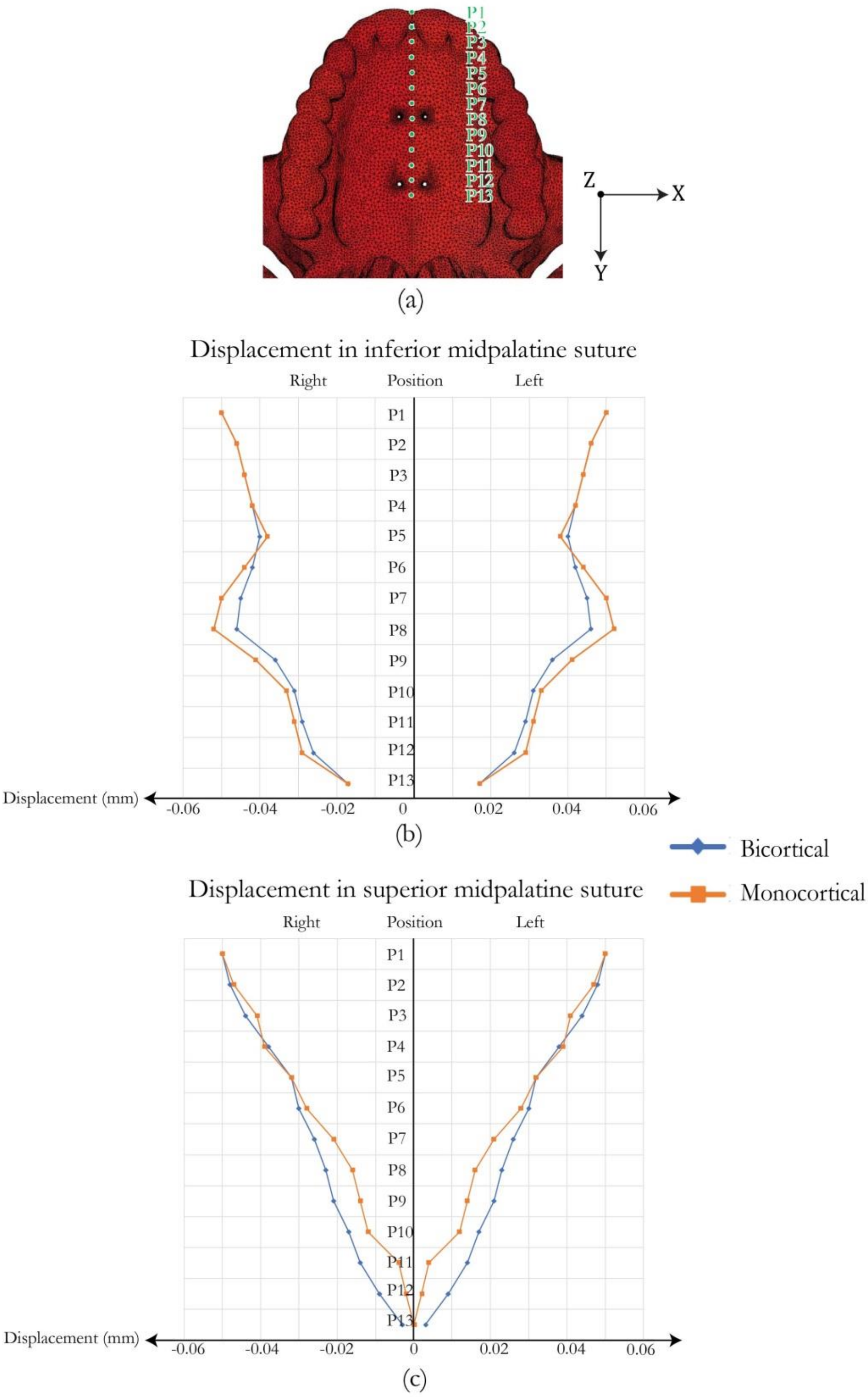

Figure 4 The displacement amount and pattern in partly ossified midpalatine suture case of monocortical and bicortical placement technique; (a) reference measuring point to record amount of displacement (P1-P13), (b) graph representing displacement in each reference point along inferior midpalatine suture, (c) graph representing displacement along superior midpalatine suture

Note: The negative and positive values in (b) and (c) graph representing displacement to the right and left, respectively

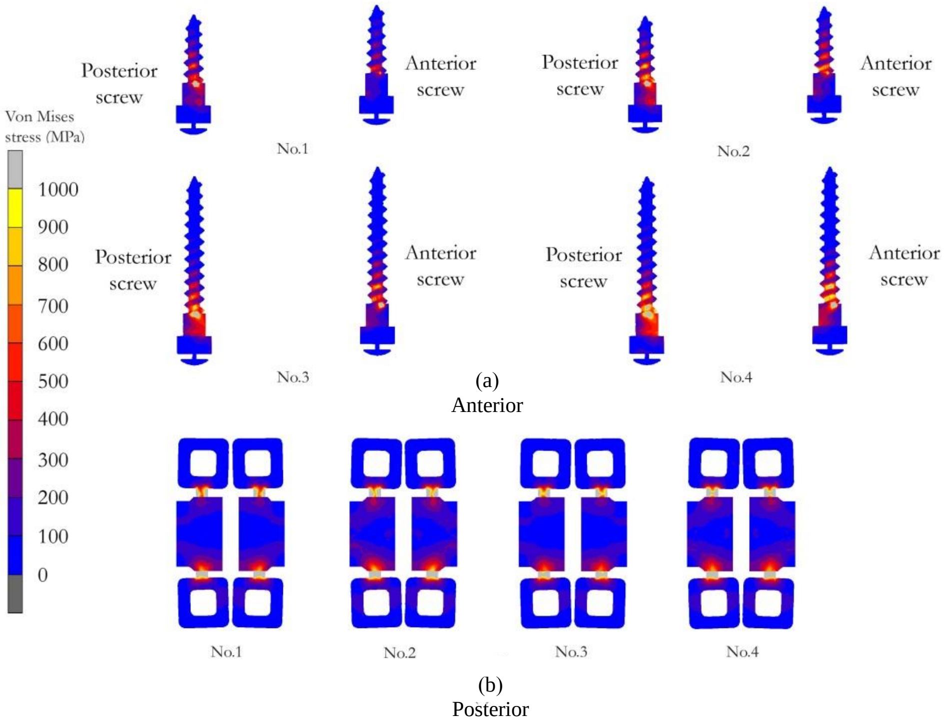

Figure 5 The von Mises stress distribution pattern in B-RPE appliance; (a) stress concentration pattern at miniscrews, (b) stress concentration at expander

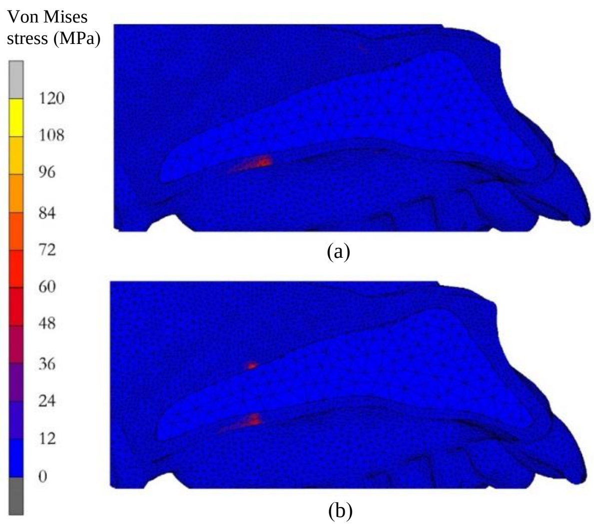

Figure 6 The von Mises stress distribution in partly ossified midpalatine suture model; (a) case No.1 the stress concentrate in inferoanterior region of midpalatine suture at palatine bone, (b) case No.3 the stress concentrate in both superoanterior and inferoanterior region of midpalatine suture at palatine bone

3.4 Elastic strain

Elastic strain was used to measure the stability of miniscrew placement in bone. In order to monitor the stability, the elastic strain was observed along coronal and sagittal plane of miniscrews. Partial ossified cases presented the higher elastic strain than complete ossified cases. In addition, the monocortical placement presented the higher elastic strain values than bicortical placement technique during partly ossified stage. There was no significant in magnitude observed in complete ossified cases, as shown in Table 5. In monocortical placement, the elastic strain highly concentrated on marginal bone and bone surrounded screw tip. For bicortical placement, the elastic strain was high around marginal bone and upper intraosseous portion.

High elastic strain at screw tip accumulated on medial side of monocortical placement miniscrews in coronal planes, as shown in Figure 7(a) and 7(b). In sagittal plane, the elastic strain at screw tip accumulated on anterior side of anterior miniscrews and posterior side of posterior miniscrews, as shown in Figure 7(c).

Table 5 Elastic strain

Case No.	Elastic strain (με)
1	55,174
2	51,539
3	53,491
4	52,295

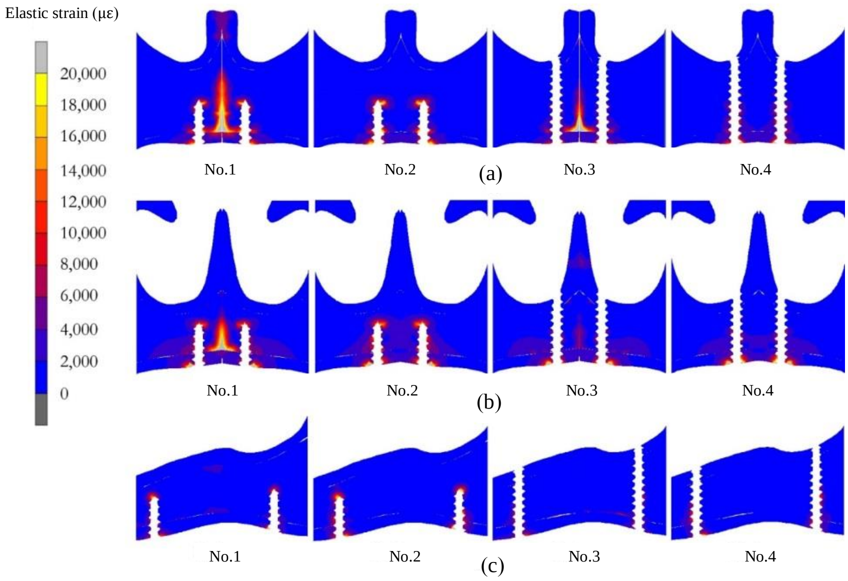

Figure 7 The elastic strain pattern at peri-implant site in all models; (a) coronal plane cross-sectional at anterior miniscrews, (b) coronal plane cross-sectional at posterior miniscrews, (c) sagittal plane cross-sectional site along miniscrews placement site

4. DISCUSSION

This study used FE method to analyze biomechanical performance between monocortical and bicortical miniscrew placement using B-RPE. The developed FE models were derived from clinical work, which suture was assigned varied maturation stage, and contact condition, which separate the suture only in maxilla midpalatine suture region. In addition, depth miniscrew of placement and force applying position was based on practical situations. Therefore, there is no previous work (Seong et al., 2018; Lee et al., 2017; Lee et al., 2014; Ludwig et al., 2013; Provatidis et al., 2008; Jafari et al., 2003), which set the condition similar to this study.

Due to the limitation of midpalatine suture information, i.e., mechanical properties and contact properties. This study simulated resemble reality situation and clinical application by modeling the midpalatine suture maturation stage classified by Angelieri et al. (2013), who described the properties of midpalatine suture in each stage. Study of Tonello et al. (2017) has reported the clinical success of using conventional maxillary expansion in maturation stage A, B, and C treatment. However, the stage D and E are a situation that the conventional maxillary expansion cannot be effectively used. B-RPE was designed to achieve the limited performance of conventional maxillary expansion. Therefore, this study selected to assign midpalatine suture with maturation stage D and E.

Previous study by Lee et al. (2014) has reported parallel displacement from applying B-RPE, however, in this study both monocortical and bicortical miniscrew placement techniques showed the unparalleled of suture line in coronal plane. This made buccal bending in coronal plane, which the inferior midpalatine suture was displaced more than superior midpalatine suture. In addition, this study also found that the anterior part of palate was expanded more than posterior part of palate, which make the “V” shape gap expansion. Parallel pattern could well produce the stability in treatment outcome. This is because the parallel of both sides of suture will enhance equivalent bone growth along the suture line in superior and inferior midpalatal suture. It reduced the malinclination of teeth, which also reduced the buccal tipping. Buccal tipping of posterior teeth can cause non-axial loading and produce high stress in cervical portion of teeth leading to non-carious cervical wear (Michael et al., 2009).

The materials properties assigned to this FE study were employed in linearly elastic model. The stress magnitude beyond yield point would still under linear relationship. The observed high stress level over yield stress level was due to this issue.

The values of von Mises stress at miniscrew was high in monocortical miniscrew placement technique, even in partly ossified midpalatine suture cases. The von Mises stress exhibited on monocortical miniscrews placement was 48.05% greater than bicortical miniscrews placement. Results from this study corresponded well to Lee et al. (2017), who presented the difference of von Mises stress between both techniques around 47.94%.

The von Mises stress concentrated highly in neck and upper intraosseous part of miniscrews, and also in the connecting arms of expander. This could be risk region, which lead to device and appliance deformation or failure. (Nojima et al., 2018).

The outcome of treatment in partly ossified model in both monocortical and bicortical placement types can expand the midpalatine suture at maxilla bone. For midpalatine suture at palatine bone where the suture was completely ossified, the von Mises stress concentrated at anterior margin of palatine bone in midpalatal suture. Although the von Mises stress exhibited on bone was lower than ultimate tensile strength of cortical bone, which is 135 MPa (Yu et al., 2015), however, it implied that further activation can lead to higher stress level for breaking palatine midpalatal suture.

This study also found that the high von Mises stress concentrated at midpalatine suture only around site of miniscrew placement in completed ossified suture which correspond to the finding of Boryor et al. (2013), who conduct a new proposed maxillary expansion treatment method with fused intermaxillary suture in cadaver. Therefore, there is a chance that midpalatine suture line may not be expanded. This is because the complete ossified suture has the mechanical property close to cortical bone. Higher magnitude of force is required to expand the suture, which excessive magnitude may cause device and appliances failure and unable to perform further activation. This will essentially undergo corticopuncture to relief the force required to eventually success maxillary expansion (Suzuki et al, 2018)

Indicated factor used to predict failure of treatment is microdamages in peri-implant bone. If the elastic strain exceeds the physiologic stage of bone according to Frost' mechanostat's theory (Frost, 1994), it can cause bone resorption around miniscrew. This subsequently makes miniscrew loosen and failure. Previous study by Albogha et al. (2016) recommended that the monitoring parameter of miniscrew failure should be elastic strain rather than von Mises stress. In this study, the maximum elastic strain exceed the physiologic threshold. It then implied resorption of bone in high elastic strain region.

The elastic stain distribution in monocortical model showed high strain level at medial of peri-implant tip and lateral initial cortical margin in coronal plane and at screw tip accumulated on anterior side of anterior miniscrews and posterior side of posterior miniscrews in sagittal plane. This may lead to the buccal and antero-posterior tipping of miniscrew within bone. In the bicortical miniscrew placement technique, the strain concentrated only on bone surrounded upper intraosseous portion with lower value than monocortical placement technique in partly ossified stage. As a result, high stability was achieved. The tipping of miniscrew has change angulation of miniscrew and the direction of force, which affects in stress distribution at peri-implant site (Perillo et al., 2015). This would reduce the withstanding load prior miniscrew failure (Pickard et al., 2010).

FE analysis in orthodontics treatment is useful to investigate biomechanics, which cadaver and clinical studies cannot be performed. For example, monitoring miniscrew motion in bone layer is not possible to do in clinical experiment. Moreover, FE analysis allows complex contact and boundary conditions of orthodontics model in various conditions to be studied.

The finding from this study revealed that the bicortical placement was obviously more advantage than monocortical placement technique. However, there are several placement sites which may affected the result. Thus, the further study regarding to this issue may be explored in order to provide best outcome.

5. CONCLUSION

This study performed comparative analysis between monocortical and bicortical placement technique of B-RPE devices by a means of FE analysis. From the results, both monocortical and bicortical placement techniques in B-RPE can potentially separate the partially ossified midpalatine suture. The bicortical placement technique increases the stability of miniscrews, which decrease the risk of screw deformation and promoting more favorable parallel displacement of maxillary structure. Neither monocortical nor bicortical placement technique using B-RPE can expand the completed ossified midpalatine suture, nevertheless, it requires higher force than partly ossified stage. Based on computational finding, bicortical placement techniques should be performed which would produce the good clinical outcome.

In addition, the further studies could investigate biomechanical effect of maxillary structure and B-RPE with bicortical technique in vary placement site of miniscrew. This would well support the clinicians for proper placement guidance.

REFERENCES

Albogha, M. H., Kitahara, T., Todo, M., Hyakutake, H., and Takahashi, I. (2016). Maximum principal strain as a criterion for prediction of orthodontic mini-implants failure in subject-specific finite element models. *Angle Orthodontist*, 86(1), 24-31.

Alhammadi, M. S., Halboub, E., Fayed, M. S., Labib, A., and El-Saaidi, C. (2018). Global distribution of malocclusion traits: A systematic review. *Dental Press Journal of Orthodontics*, 23(6), e1-e10.

Angelieri, F., Cevidanes, L. H. S., Franchi, L., Gonçalves, J. R., Benavides, E., and McNamara Jr., J. A. (2013). Midpalatal suture maturation: classification method for individual assessment before rapid maxillary expansion. *American Journal of Orthodontics and Dentofacial Orthopedics*, 144(5), 759-769.

Baccetti, T., Franchi, L., Cameron, C. G., and McNamara Jr., J. A. (2001). Treatment timing for rapid maxillary expansion. *Angle Orthodontist*, 71(5), 343-350.

Baysal, A., Uysal, T., Veli, I., Ozer, T., Karadede, I., and Hekimoglu, S. (2013). Evaluation of alveolar bone loss following rapid maxillary expansion using cone-beam computed tomography. *Korean Journal of Orthodontics*, 43(2), 83-95.

Boryor, A., Hohmann, A., Wunderlich, A., Geiger, M., Kilic, F., Kim, K. B., Sander, M., Böckers, T., and Sander, C. (2013). Use of a modified expander during rapid maxillary expansion in adults: an in vitro and finite element study. *International Journal of Oral and Maxillofacial Implants*, 28(1), e11-e16.

Carvalho Trojan, L., Andrés González-Torres, L., Claudia Moreira Melo, A., and Barbosa de Las Casas, E. (2017). Stresses and strains analysis using different palatal expander appliances in upper jaw and midpalatal Suture. *Artificial Organs*, 41(6), E41-E51.

Choi, T. H., Kim, B. I., Chung, C. J., Kim, H. J., Baik, H. S., Park, Y. C., and Lee, K. J. (2015). Assessment of masticatory function in patients with non-sagittal occlusal discrepancies. *Journal of Oral Rehabilitation*, 42(1), 2-9.

Corega, C., Corega, M., Băciuţ, M., Vaida, L., Wangerin, K., Bran, S., and Băciuţ, G. (2010). Bimaxillary distraction osteogenesis--an effective approach for the transverse jaw discrepancies in adults. *Chirurgia (Romania)*, 105(4), 571-575.

Erverdi, N., Okar, I., Kücükkeles, N., and Arbak, S. (1994). A comparison of two different rapid palatal expansion techniques from the point of root resorption. *American Journal of Orthodontics and Dentofacial Orthopedics*, 106(1), 47-51.

Farnsworth, D., Rossouw, P. E., Ceen, R. F., and Buschang, P. H. (2011). Cortical bone thickness at common miniscrew implant placement sites. *American Journal of Orthodontics and Dentofacial Orthopedics*, 139(4), 495-503.

Frost, H. M. (1994). Wolff's law and bone's structural adaptations to mechanical usage: an overview for clinicians. *Angle Orthodontist*, 64(3), 175-188.

Jafari, A., Shetty, K. S., and Kumar, M. (2003). Study of stress distribution and displacement of various craniofacial structures following application of transverse orthopedic forces--a three-dimensional FEM study. *Angle Orthodontist*, 73(1), 12-20.

Kim, K. B., and Helmkamp, M. E. (2012). Miniscrew implant-supported rapid maxillary expansion, *Journal of Clinical Orthodontics*, 46(10), 608-612.

Lee, R. J., Moon, W., and Hong, C. (2017). Effects of monocortical and bicortical mini-implant anchorage on bone-borne palatal expansion using finite element analysis. *American Journal of Orthodontics and Dentofacial Orthopedics*, 151(5), 887-897.

Lee, H. K., Bayome, M., Ahn, C. S., Kim, S. H., Kim, K. B., Mo, S. S., and Kook, Y. A. (2014). Stress distribution and displacement by different bone-borne palatal expanders with micro-implants: a three-dimensional finite-element analysis. *European Journal of Orthodontics*, 36(5), 531-540.

Lee, H., Ting, K., Nelson, M., Sun, N., and Sung, S. J. (2009). Maxillary expansion in customized finite element method models. *American Journal of Orthodontics and Dentofacial Orthopedics*, 136(3), 367-374.

Ludwig, B., Baumgaertel, S., Zorkun, B., Bonitz, L., Glasl, B., Wilmes, B., and Lisson, J. (2013). Application of a new viscoelastic finite element method model and analysis of miniscrew-supported hybrid hyrax treatment. *American Journal of Orthodontics and Dentofacial Orthopedics*, 143(3), 426-435.

MacGinnis, M., Chu, H., Youssef, G., Wu, K. W., Machado, A. W., and Moon, W. (2014). The effects of micro-implant assisted rapid palatal expansion (MARPE) on the nasomaxillary complex-a finite element method (FEM) analysis. *Progress in Orthodontics*, 15(1), 52.

Michael, J. A., Townsend, G. C., Greenwood, L. F., and Kaidonis, J. A. (2009). Abfraction: separating fact from fiction. *Australian Dental Journal*, 54(1), 2-8.

Mosleh, M. I., Kaddah, M. A., Abd Elsayed, F. A., and Elsayed, H. S. (2015). Comparison of transverse changes during maxillary expansion with 4-point bone-borne and tooth-borne maxillary expanders. *American Journal of Orthodontics and Dentofacial Orthopedics*, 148(4), 599-607.

Nojima, L. I., Nojima, M. D. C. G., da Cunha, A. C., Guss, N. O., and Sant'anna, E. F. (2018) Mini-implant selection protocol applied to MARPE. *Dental Press Journal of Orthodontics*, 23(5), 93-101.

Northway, W. M., and Meade Jr., J. B. (1997). Surgically assisted rapid maxillary expansion: a comparison of technique, response, and stability. *Angle Orthodontist*, 67(4), 309-320.

Perillo, L., Jamilian, A., Shafieyoon, A., Karimi, H., and Cozzani, M. (2015). Finite element analysis of miniscrew placement in mandibular alveolar bone with varied angulations. *European Journal of Orthodontics*, 37(1), 56-59.

Persson, M., and Thilander, B. (1997). Palatal suture closure in man from 15 to 35 years of age. *American Journal of Orthodontics*, 72(1), 42-52.

Pickard, M. B., Dechow, P., Rossouw, P. E., and Buschang, P. H. (2010). Effects of miniscrew orientation on implant stability and resistance to failure. *American Journal of Orthodontics and Dentofacial Orthopedics*, 137(1), 91-99.

Provatidis, C. G., Georgiopoulos, B., Kotinas, A., and McDonald, J. P. (2008). Evaluation of craniofacial effects during rapid maxillary expansion through combined in vivo/in vitro and finite element studies. *European Journal of Orthodontics*, 30(5), 437-448.

Seong, E. H., Choi, S. H., Kim, H. J., Yu, H. S., Park, Y. C., and Lee, K. J. (2018). Evaluation of the effects of miniscrew incorporation in palatal expanders for young adults using finite element analysis. *Korean Journal of Orthodontics*, 48(2), 81-89.

Soboleski, D., McCloskey, D., Mussari, B., Sauerbrei, E., Clarke, M., and Fletcher, A. (1997). Sonography of normal cranial sutures. *American Journal of Roentgenology*, 168(3), 819-821.

Suzuki, S. S., Braga, L. F. S., Fujii, D. N., Moon, W., and Suzuki, H. (2018). Corticopuncture facilitated microimplant-assisted rapid palatal expansion. *Case Reports in Dentistry*, 1392895.

Tonello, D. L., Ladewig, V. D. M., Guedes, F. P., Ferreira Conti, A. C. D. C., Almeida-Pedrin, R. R., and Capelozza-Filho, L. (2017). Midpalatal suture maturation in 11- to 15-year-olds: A cone-beam computed tomographic study. *American Journal of Orthodontics and Dentofacial Orthopedics*, 152(1), 42-48.

Winsauer, H., Vlachojannis, J., Winsauer, C., Ludwig, B., and Walter, A. (2013). A bone-borne appliance for rapid maxillary expansion. *Journal of Clinical Orthodontics*, 47(6), 375-381.

Yu, J. C., Martin, A., Ho, B., and Masoumy, M. (2015). Fixation Techniques. In *Ferraro's Fundamentals of Maxillofacial Surgery* (Taub, P. J., Patel, P. K., Buchman, S. R., and Cohen, M. N., eds.), pp. 103-113. New York: Springer.