Original Article

Fixed versus Removable Appliance for Palatal Expansion; A 3D Analysis Using the Finite Element Method

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Abstract

Objective: Several appliances have been used for palatal expansion for treatment of posterior cross bite. The purpose of this study was to evaluate the stress induced in the apical and crestal alveolar bone and the pattern of tooth displacement following expansion via removable expansion plates or fixed-banded palatal expander using the finite element method (FEM) analysis.

Materials and Methods: Two 3D FEM models were designed from a mesiodistal slice of the maxilla containing the upper first molars, their periodontium and alveolar bone. Two palatal expanders (removable and fixed) were modeled. The models were designed in SolidWorks 2006 and then transferred to ANSYS Workbench. The appliance halves were displaced 0.1 mm laterally. The von Mises stress in the apical, crestal, and PDL areas and also the vertical displacement of the cusps (palatal and buccal) was were evaluated.

Results: The total PDL stress was 0.40003 MPa in the removable appliance (RA) model and 4.88e-2 MPa in the fixed appliance (FA) model and the apical stress was 9.9e-2 and 1.17e-2 MPa, respectively. The crestal stress was 2.99e-1 MPa in RA and 7.62e-2 MPa in the FA. The stress in the cortical bone crest was 0.30327 and 7.9244e-2 MPa for RA and FA, respectively and 3.7271 and 7.4373e-2 MPa in crestal area of spongy bone, respectively. The vertical displacement of the buccal cusp and palatal cusp was 1.64e-2 and 5.90e-2 mm in RA and 1.05e-4 and 1.7e-4 mm in FA, respectively.

Conclusion: The overall stress as well as apical and crestal stress in periodontium of anchor teeth was higher in RA than FA; RA elicited higher stress in both cortical and spongy bone. The vertical displacement of molar cusps was more in removable than fixed palatal expander model.

Key Words: Orthodontics; Palatal Expansion Technique; Finite Element Method

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INTRODUCTION

One of the most prevalent occlusal discrepancies is posterior crossbite which is a consequence of transverse discrepancy between maxillary and mandibular dental arches. Maxillary constriction can be skeletal, dental or a combination of both. The prevalence of posterior crossbite in primary and mixed dentitions has been reported to be 8 to 23 % [1]. This discrepancy can cause functional shifting which affects jaw growth and increases the risk of facial asymmetry and cranio-mandibular disorders [2-4]. Additionally, maxillary constriction leads to space deficiency in the dental arch that results in crowding, increases the risk of tooth impaction or aggravates occlusal disharmony [5, 6]. Various treatment modalities have been proposed and used for correction of posterior crossbite via orthodontic or orthopedic maxillary expansion. These protocols are generally divided into rapid maxillary expansion (RME) and slow maxillary expansion (SME) based on the activation intervals and force exerted by the appliances [1, 7]. Several appliances are used as palatal expanders. Fixed appliances such as Haas and Hyrax with jackscrews can be used for both SME and RME [8, 9]; while, removable expansion plates and quad helix are designed for SME [10]. According to two systematic reviews, the available evidence on the advantages of one treatment over the other one is insufficient now and more studies are needed [11, 12]. In RME treatment, the expansion screw is activated one or two times a day which is 0.25 – 0.5 mm expansion by about 100 N force [13]. SME appliances with screws are activated once or twice a week; which exert about a 20 N force [8]. Thus, SME can elicit more efficient skeletal changes and more stable results by allowing more time for adaptation [8]. The bone of the mid-palatal suture responds to compressive and tensile forces. However, since the expansive force is directed to the teeth, dental movement and alterations in tooth inclination relative to the supporting bone structure is inevitable. Although the most desirable type of tooth movement is bodily movement, palatal expansion leads to some extent of molar tipping [14]. It is believed that the skeletal-to-dental movement ratios vary according to type of expander appliance and the protocol of activation [13].

Accordingly, it is important to understand the pattern of stress distribution along the maxillary sutures as well as throughout the alveolar bone induced by palatal expanders. It is also imperative to know the pattern of tooth movement, improve the appliance design and minimize the adverse effects. Clinical studies have some limitations in illustrating the biomechanical effects of palatal expansion; conventional methods such as photoelastic and strain gauges cannot identify the exact sites of stress concentration in the orthopedic response [15, 16].

The finite element method (FEM) has been successfully applied for the biomechanical study of stress and strain response to foreign forces in living structures [17]. This method has proven its efficiency in answering a wide range of questions from basic to clinical [18-23]. With regard to the issue of orthopedic palatal expansion there are few FEM studies that address stress distribution in RME along the midpalatal and craniofacial sutures [15, 24, 25]. However, none of them compare different expander appliances and the patterns of tooth movement during expansion. This finite element study was done to evaluate the stress induced in the apical and crestal alveolar bone following the same amount of displacement induced by removable expansion plates and fixed appliances.

MATERIALS AND METHODS

Three dimensional finite element method (3D FEM) was selected for the analysis. Two 3D FEM models were designed from a mesio-distal slice of the maxilla containing the upper first molars. The first model consisted of the left and right first molars, their PDL, a palatal expander and a mesio-distal slice of the maxillae. The difference between the two models was the design of the expander. In the first model, the expander was a removable appliance and the other model contained a fixed appliance.

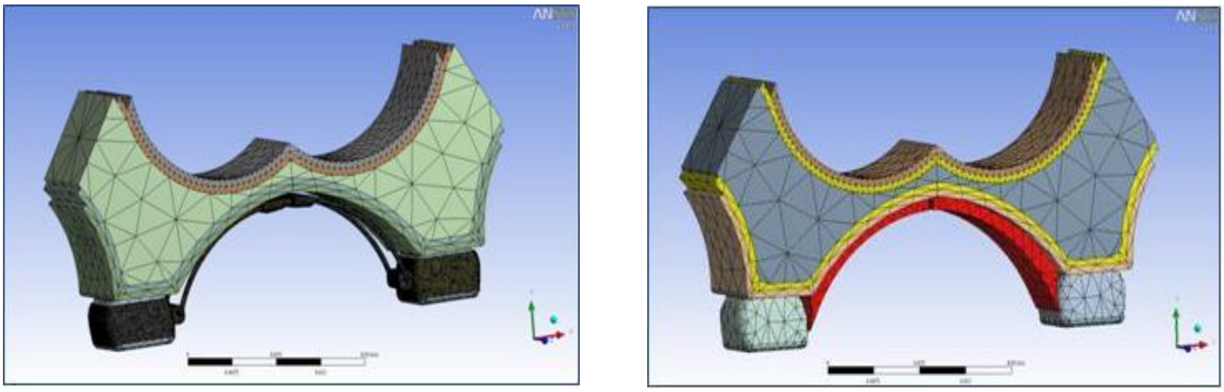

Fig1. The meshed models: fixed appliance model (left), removable appliance model (right)

Contact elements were defined so that the contact point of the removable appliance with the palatal side of the molars was inseparable, simulating the contact of an Adam's clasp to the palatal surface of the molar crown.

The models were designed in SolidWorks 2006 (Concord, Massachusetts, USA) and then transferred to ANSYS Workbench Ver. 11(Canonsburg PA, USA) for the analysis. Meshing was done by the Workbench meshing program.

Meshed models contained 260,551 nodes and 129,570 elements in the removable expansion model and 530,806 nodes and 325,159 elements in the fixed palatal expansion model (Figure 1). The anterior and posterior surfaces of each model were restrained. The mechanical properties of the materials used are presented in Table 1. The appliance halves were displaced 0.1 mm laterally. The von Mises stress in the apical, crestal, and PDL and also the vertical displacement of the cusps (palatal and buccal) of the first maxillary molars were evaluated.

Table 1. Mechanical properties of the materials used in models

	Young's Modulus (MPa)	Poisson's Ratio
Tooth	20300	0.26
PDL	0.667	0.49
Spongy Bone	13400	0.38
Cortical Bone	34000	0.26
Stainless Steel	200000	0.3
Acrylic	23000	0.4

Table 2. Levels of stress induced in models with removable and fixed palatal expanders in MPa.

	Removable appliance (e-2)	Fixed appliance (e-2)
In crestal region of PDL	29.9	7.62
In apical region of PDL	9.90	1.17
Overall PDL	40.00	4.88
In cortical bone	30.327	7.4373
In spongy bone	372.71	7.4373

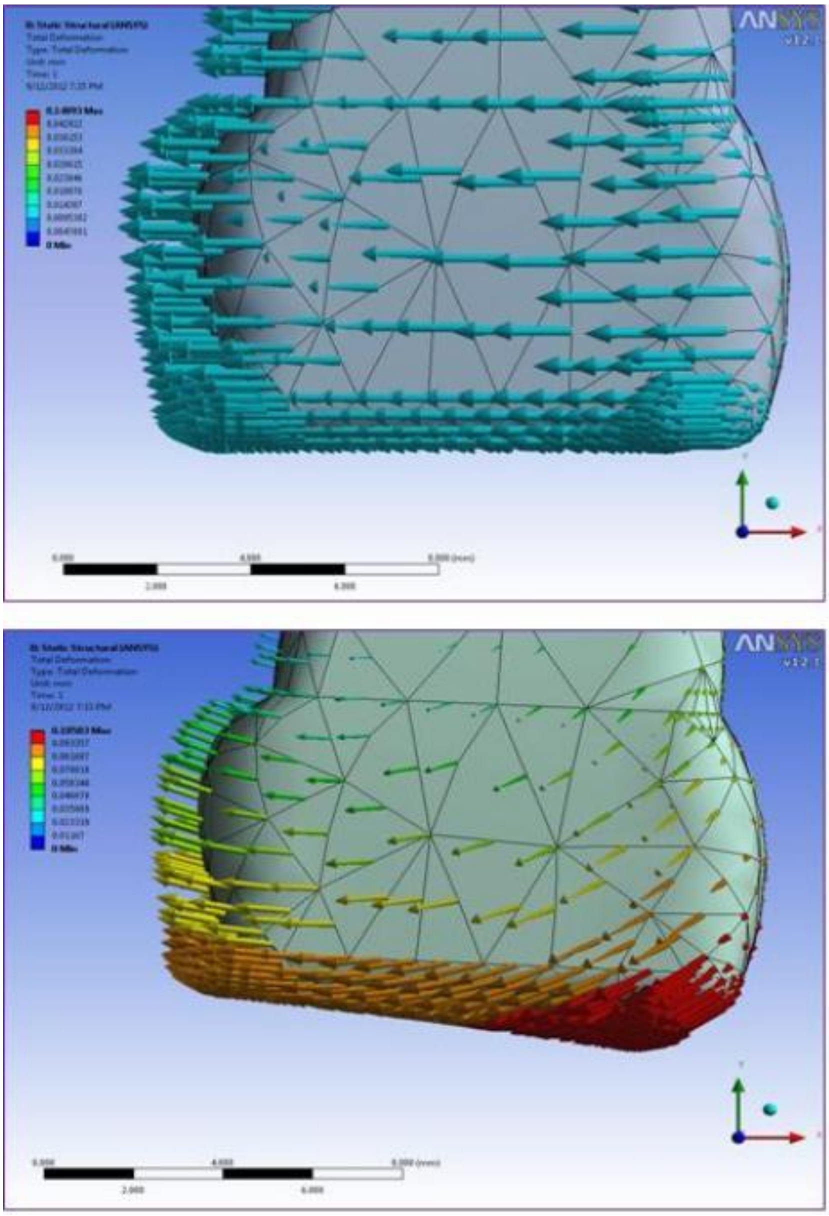

Fig 2. Displacement manner in the fixed appliance model (top); the removable appliance model (bottom).

RESULTS

Numeric findings are shown in Tables 2 and 3.

Stress:

The von Mises stress in the PDL was 0.40003 MPa in the model with the removable appliance and 4.88e-2 MPa in the fixed appliance model. The apical stress was 9.9e-2 MPa in the removable model and 1.17e-2 MPa in the fixed one.

The crestal stress was 2.99e-1 MPa in the removable appliance model and 7.62e-2 MPa in the fixed model (Table 2). Crestal stress was 0.30327 MPa in the cortical crest bone in removable appliance and 7.9244e-2 MPa in the fixed appliance. These findings were 3.7271 MPa in the removable and 7.4373e-2 MPa in the fixed appliance when measured in the spongy bone area of the crest.

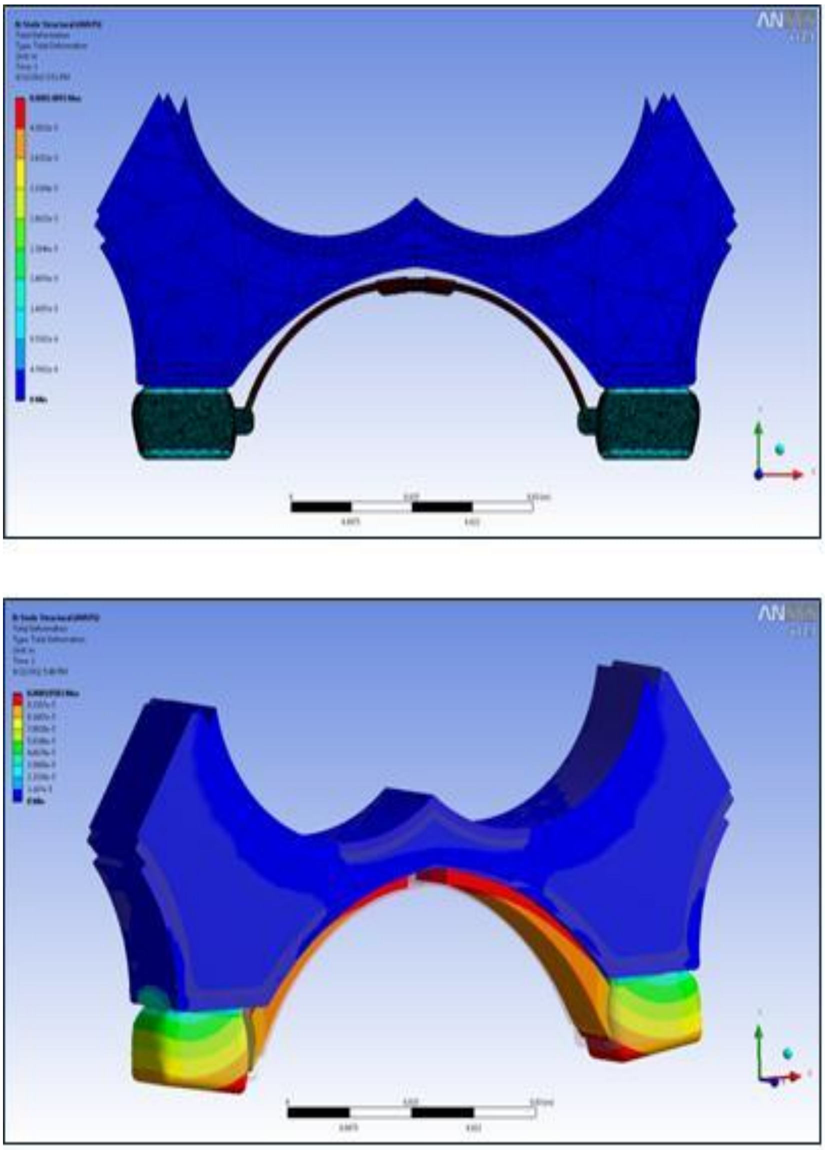

Fig 3. Total displacement produced in the fixed appliance model (top); the removable appliance model (bottom).

Displacement:

The vertical displacement measured at the buccal cusp of the first molar (inferior-superiorly) was 1.64e-2 mm in the removable and 1.05e-4 mm in the fixed appliance model (Table 3). This displacement in the palatal cusp was 5.90e-2 mm in the removable and 1.7e-4 mm in the fixed appliance model (Figures 2 and 3).

Table 3. Vertical displacement of various points in the crown of a modeled tooth in a model under expansion by a removable and fixed appliance (in mm).

	Removable appliance (e-2)	Fixed appliance (e-4)
Buccal cusp	1.64	1.05
Palatal cusp	5.90	1.7

DISCUSSION

With regard to the amount of expansion-induced stress in the apical region of the anchor tooth, the results obtained from this FEM study indicated that expansion via a removable appliance (RA) produced excessive stress at the apical and crestal regions while the stress was relatively low in fixed appliances (FA, Table 2). With regard to the hypothesis that more molar tipping occurs by RA, this high apical stress can be attributed to apical displacement of the root in uncontrolled tipping type of tooth movement. A high degree of tipping is more obvious when the vertical movement of buccal and palatal cusps were compared in removable and fixed models. As can be seen in Table 3, buccal cusps of the molars were displaced about 162.95 e-4mm more in RA using FA in the apico-coronal direction. Similarly, the palatal cusp moved about 588.30e-4 mm more in the same direction using RA. Moreover, the arrows which were representative of displacement (Figure 2) depicted a harmonious pattern and parallel directions throughout the teeth in FA; while in RA the inclination of the arrows changed smoothly from buccal to palatal cusps of the tooth. Two scopes can be extrapolated from these results: the type of tooth movement during expansion (bodily vs. tipping) and direction or vertical tooth movement. According to finite element analysis of this study, more buccal tipping occurs in molars undergoing expansion with RA while banded expanders induced more bodily buccal movement of molars. Although the most desirable tooth movement during palatal expansion is bodily movement, previous studies on this issue stated some degrees of buccal crown tipping of anchor teeth during expansion [6, 26-28]. This tipping is inevitable since the expansive force is delivered to the crowns of the teeth away from center of resistance. The reported amount of tipping is various. Handelman et al. [28] reported 5.1° of maxillary molar buccal tipping after expansion and Chung stated that 4.3% of inter-molar expansion after treatment by the Haas appliance was due to buccal crown tipping [29]. The degree of tipping depends on various factors; some studies compared tooth-born appliances (hyrax) and tooth-tissue born (Haas) appliances and observed tipping in both types but more in banded relative to bonded ones; albeit the difference was not significant in some studies [26, 30]. With regard to RA, it can be speculated that the force delivered to teeth by acrylic plate cannot produce a force necessary for bodily movement because there is no constant contact between the acrylic plate and tooth surface. The acrylic plate can slide on the tooth and the location of force exertion varies with time. The pattern of contact depends on the amount of adaptation of the acrylic plate and tooth surface. However, in FA, the bands have a wrap-around effect on the anchor teeth. The manner of tooth-band contact which is provided by the cement layer and the rigid type of band-appliance connection neutralizes the tipping induced by the screw - wire force application. From another point of view, the buccal tipping of anchor tooth can lead to lingual tipping as a consequence of relapse after retention time. For example McNamara et al. [27] reported 5° lingual tipping in the crown of upper molars and 6° in lower molars in long term observation after expansion phase. With regard to the results of vertical dimension, both buccal and lingual cusps showed vertical displacement in the same directions. It can be concluded that palatal expansion induced extrusive force on anchor teeth and the extrusion is more prominent in RA than FA. The importance of this issue is more obvious in patients with vertical growth patterns and opens bite tendency in which the preservation of the bite is more crucial [31, 32]. Considering the total stress distribution throughout the periodontium, the results of this study revealed that higher levels of stress were induced in periodontium of anchor teeth in RA than in PDL of anchor teeth of FA with the same expansion force (Table 2). The difference in supporting structures of these appliances is worth consideration. With the same amount of expansion produced by RA and FA, the entire force is applied to the anchor tooth (molar) in FA but it is not the same in RA despite the presence of a wide area of acrylic-palatal tissue contact. However, the amount of force even in RA was not above the PDL level of stress under routine orthodontic forces [33]. Previous studies explained the force exerted by palatal expanders produced compression areas in PDL of supporting teeth. Subsequently, alveolar bone resorption occurred on the buccal side; which in turn led to tooth movement in the same direction [34]. Odenrick et al. [35] confirmed that tooth-born palatal expanders were more iatrogenic from the periodontal health standpoint and caused more root resorption in the anchor teeth. Comparing the stress induced in cortical and spongy bone in the crestal region, our results indicated that RA exerted a higher level of stress in both bone types than FA. Although in the FA model the amount of stress in both types was approximately similar, in RA, the stress of spongy bone was nearly ten times more than that of cortical bone. Excessive tooth movement in the buccal direction puts high stress on the buccal plate of alveolar bone, especially in the crestal region and decreased buccal bone plate thickness has been reported following RME with banded and bonded expanders [36] as well as after SME [37]. These findings were observed only in anchor teeth (for example in the first molar and first premolar not in canine or second premolar). This reduction was more prominent in tooth-born (hyrax) relative to tooth and tissue-born (Haas) appliances. Garib et al. [36] believed that the lingual bone plate may increase in thickness after expansion. However, since tooth and tissue-born appliances elicited compression-induced resorption in palatal plate, the lingual bone plate resorption did not increase as much as tooth-born expanders. They also reported reduction in the level of alveolar crest in buccal region of first molar and first premolars especially in mesiobuccal region of first molar; which is thinner than central and distal areas. There has been a strong correlation between excessive tooth movement and alveolar bone dehiscence reported in the literature [38, 39] and an increased rate of dehiscence following RME has been observed in various animal studies [40-42]. This issue is more debatable when comparing RME and SME because of different magnitudes of force and activation intervals. However, in comparison of FA and RA, it can be extrapolated that the expander with a higher level of stress in the crestal region (which was RA in this study) makes the alveolar bone more susceptible to resorption and dehiscence. From a more clinical point of view, several issues can be disputed. Fixed appliances are not dependent on patient compliance and therefore their results are more predictable [43]. However oral hygiene may be impaired by fixed appliances and banding can make the tooth more prone to demineralization [44]. On the other hand, when other minor tooth movements such as buccal movement of a lingually placed lateral incisor is required, it can be done simultaneously with a removable expander by inserting a Z spring in the acrylic plate. With regard to applying finite element method to analyze maxillary expansion, lseri et al. evaluated the biomechanical effect of RME on the craniofacial complex and measured the stress induced and the amount of widening in circum-maxillary structures [25]. They concluded that the highest stress concentrated at the pterygoid plates of the sphenoid bone in the region close to the cranial base. In another FEM study, Gautam et al. demonstrated downward displacement and backward rotation of the maxilla and high stresses along the deep structures and the various sutures of the craniofacial skeleton following RME [15]. Lee et al. compared stress pattern distribution between two FEM models with and without patent palatal suture and concluded different patterns of stress distribution in circum-maxillary sutures [45]. However, it should be mentioned that in our study, the orthopedic effect of palatal expansion or stress distribution pattern in mid-palatal suture was not modeled and evaluated since we concentrated on the stress distribution pattern in anchored teeth and orthodontic not orthopedic effects of two types of palatal expanders (removable and fixed).

None of the above studies evaluated stresses in anchored teeth nor considered slow palatal expansion or removable appliances. Now that this study has provided fundamental information about the pattern of tooth movement in fixed and removable palatal expander appliances, further studies in clinical setups can be performed to address various aspects of this issue.

CONCLUSION

Within the limitations of this FEM study, we concluded that:

1. The degree of buccal molar tipping is higher in palatal expansion with RA than FA.
2. The crestal and apical level of stress was higher in RA than FA.
3. The overall stress in periodontium of anchor teeth was higher in RA than FA.
4. RA elicited higher stress in both cortical and spongy bone than FA.

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