J Huazhong Univ Sci Technol［Med Sci］ 34(6):621-625,2014
DOI 10.1007/s11596-014-1327-8

Comparative Characterization of Maxillary Expansion and Alternate Maxillary Expansions and Constrictions in Rats*

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Summary: The purpose of this study was to evaluate whether the cranial and circumaxillary sutures react differently to maxillary expansion (ME) and alternate maxillary expansions and constrictions (Alt-MEC) in a rat model. Twenty-two male Sprague-Dawley rats (6 weeks old) were used and divided into three groups. In ME group (n=9), an expander was activated for 5 days. In Alt-MEC group (9 animals), an alternate expansion and constriction protocol (5 day expansion and 5 day constriction for one cycle) was conducted for 2.5 cycles (25 days total). The control group comprised 4 animals with no appliances used, each of two sacrificed on day 5 and day 25 respectively. Midpalatal suture expansion or constriction levels were assessed qualitatively and quantitatively by bite-wing X-rays and cast models. Distances between two central incisors and two maxillary first molars were measured on cast models after each activation. Circumaxillary sutures (midpalatal, maxillopalatine, premaxillary, zygomaticotemporal and frontonasal suture) in each group were characterized histologically. Results showed that midpalatal suture was widened and restored after each expansion and constriction. At the end of activation, the widths between both central incisors and first molars in Alt-MEC group were significantly larger than those in ME group (P<0.05). Histologically, all five circumaxillary sutures studied were widened in multiple zones in Alt-MEC group. However, only midpalatal suture was expanded with cellular fibrous tissue filling in ME group. Significant osteoclast hyperplasia was observed in all circumaxillary sutures after alternate expansions and constrictions, but osteoclast count increase was only observed in midpalatal suture in ME group. These results suggested that cranial and circumaxillary sutures were actively reconstructed after Alt-MEC, while only midpalatal suture had active reaction after ME.
Key words: maxillary expansion; alternate maxillary expansions and constrictions; circumaxillary sutures

Maxillary expansion (ME) has been proposed since the 19th century by Angell[1] and was reintroduced by Haas and popularized in 1960s[2, 3]. ME has become a versatile technique and it clinically consists of correction of narrow arch or crossbite, elimination of dental crowding, facilitation of the eruption of the permanent canine[4], increasing the size of nasal airway[5], improving the skeletal and dental relationship[6, 7], and working as orthopedic adjunct to maxillary protraction.

The effects of ME on craniofacial complex have been extensively studied. During ME, the appliance compresses the periodontal ligament, bends the alveolar process, tips the anchor teeth and then gradually increases mean palatal widths and cross-sectional areas[8–11]. The maxilla articulates with other skull bones through the cranial and circumaxillary sutures. The forces delivered by activation of ME appliance usually exceed the sutural limit and not only split the midpalatal suture but also affect several other adjacent structures in the face and the cranium[10, 12–17]. Due to the loosening or activation of cranial and circumaxillary sutures the maxillary complex displace downward and forward[18, 19], which indicates that ME alone can be beneficial in the treatment of certain types of Class Ⅲ malocclusion, borderline malocclusions in particular[9, 10]. Even though there are still debates on use of ME in conjunction with protraction forces in orthopedic treatment of Class Ⅲ patients[20, 21], ME has generally been accepted as a routine procedure before maxillary protraction even in the absence of maxillary constriction or crowding[22, 23] because it supposedly disrupts the circumaxillary sutural system and presumably facilitates the orthopedic effect of the facemask[2, 21, 24, 25].

A repetitive weekly protocol of alternate maxillary expansions and constrictions (Alt-MEC) was presented by Liou[26] to disarticulate the circumaxillary sutures. With this protocol, the maxilla is expanded for 7 consecutive days and constricted for 7 consecutive days for a total 9 weeks. Several clinical studies combining this technique with maxilla protraction have shown that Alt-MEC can advance the maxilla efficiently not only in cleft lip and palate patients[26–28] but also in growing Class Ⅲ patients[26, 29–32]. It was hypothesized that the rationale of Alt-MEC is similar to that of tooth extraction, in which the tooth is moved buccally and lingually until it is fully loosened. The maxilla is disarticulated without being over-expanded but the circumaxillary sutures are exten-

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*This project was supported by Peking University School of Stomatology Youth Scientific Research Fund of China (No. PKUSS20120113).

sively opened, thus possibly enhancing the effect of the orthopedic face mask therapy[26, 27]. Only limited work has been done to test this assumption. Wang *et al*[33] quantitatively studied the extent of circumaxillary sutural openning on a cat model and found that after 5 weeks of Alt-MEC both sagittally and coronally running circumaxillary sutures were opened more extensively than 1 week of palatal expansion. However, histological characterizations of cranial and circumaxillary sutures after Alt-MEC are still not available. The aim of this study was to explore if there are any histological differences in cranial and circumaxillary sutures after ME and Alt-MEC.

1 MATERIALS AND METHODS

1.1 Animals

Twenty-two male Sprague-Dawley rats, 6-week-old and 120–130 g in weight, were used. Rats at this stage are in a growing phase and their first and second maxillary molars are fully erupted. They were divided into two experimental and one control groups. Eighteen animals were allocated evenly to the two experimental groups in which different protocols of maxillary expansion were employed. Four animals served as controls. All animals were weighed at the beginning and before each operation. They were raised under standardized laboratory conditions (12 h light-and-dark cycle and relative humidity). The experimental protocol was approved by the Animal Research Ethics Committee of Peking University. All experimental procedures were performed on anesthetized animals.

1.2 Experiment Procedure

The animals were anesthetized with pentobarbital sodium (40 mg/kg body weight) intraperitoneally before each operation. The experimental systems for maxillary expansion and constriction were modified based on what was described previously[34–36]. The maxillary expander (fig. 1A) and constrictor (fig. 1B) were made using 0.018-in stainless steel orthodontic wire with two helical loops and inserted into the spaces between the first and second molars lingually (fig. 1C) or buccally (fig. 1D). The initial expansion or constriction force was adjusted to 130–150 g, measured with a strain gauge (Tomy International Co., Japan). In ME group (9 animals), expansion arch was placed and kept activated daily for 5 days. In Alt-MEC group (9 animals), repetitive alternate maxillary expansions and constrictions lasted 25 days, commencing with expansion daily for the first 5 days. Subsequently, maxillary constrictor was used and kept activated daily for 5 days. This expansion and constriction protocol was repeated for another 10 days followed by maxillary expansion for the last 5 days.

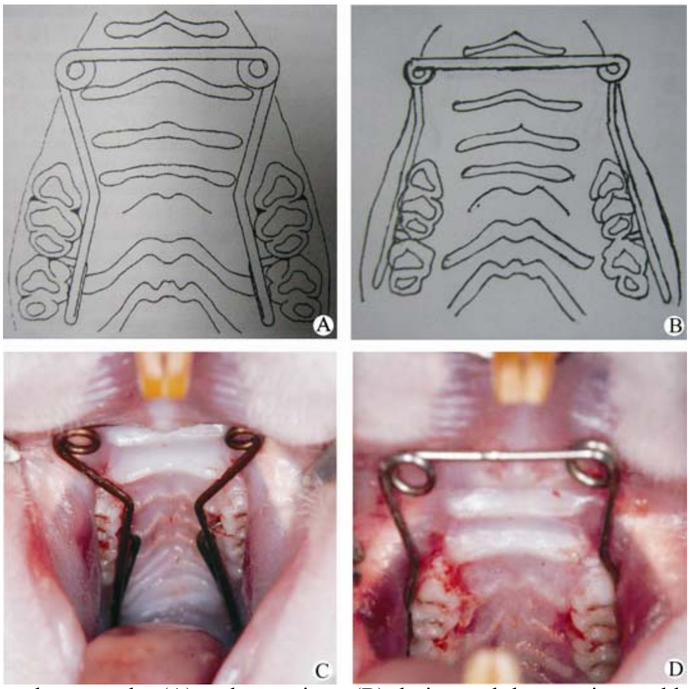

Fig. 1 Schematic drawings illustrate the expander (A) and constrictor (B) design and they are inserted between the first and second molars. Intraoral photographs of the expander (C) and constrictor (D) are shown when they are placed in rats.

1.3 Occlusal Radiographs and Cast Analysis

To qualitatively and quantitatively assess the effects of two different maxillary expansion protocols on midpalatal suture expansion and arch expansion, occlusal radiographs and cast models were taken before activation (T0), after 5 days of ME (T1) in two experiment groups, after one cycle (T2) of expansion (E) and constriction (C), after 1.5 cycles (T3, E-C-E), after 2 cycles (T4, E-C-E-C) and after 2.5 cycles (T5, E-C-E-C-E) in Alt-MEC group. The distances between two central incisors and two maxillary first molars were measured on cast models using a calibrated digital sliding caliper with an accuracy of 0.01 mm.

1.4 Histological Preparation and Analysis

All animals in experimental groups were sacrificed with an overdose of ketamin-xylazine injection at the end of the experiment. Two animals in control group were sacrificed on day 5 and 25, respectively. After sacrificing, the skeleton of the nasomaxillary complex of animals was preserved in 4% formalin for further examination and histological staining. The maxilla including the five cranial and circumaxillary sutures was dissected from all control and experimental animals. The circumaxillary sutures selected were classified into four groups[16, 33]: (1) sutures running sagittally and articulating directly to the maxilla: midpalatal suture; (2) sutures running coronally and articulating directly to maxilla: maxillopalatine and premaxillary suture; (3) sutures running sagittally and articulating indirectly to maxilla: zygomaticotemporal suture; (4) sutures running coronally and articulating indirectly to maxilla: frontonasal suture (fig. 2). For morphological observation, the fixed specimens were demineralized in 0.5 mol/L EDTA for 20 days at 4°C and then embedded in paraffin for hematoxylin and eosin (HE) staining. Tartrate resistant acid phosphatase staining (TRAP) was used for osteoclast staining. Specimens were embedded in OCT (Tissue Tek, Miles Laboratories, Naperville, USA) for frozen sections instead of paraffin.

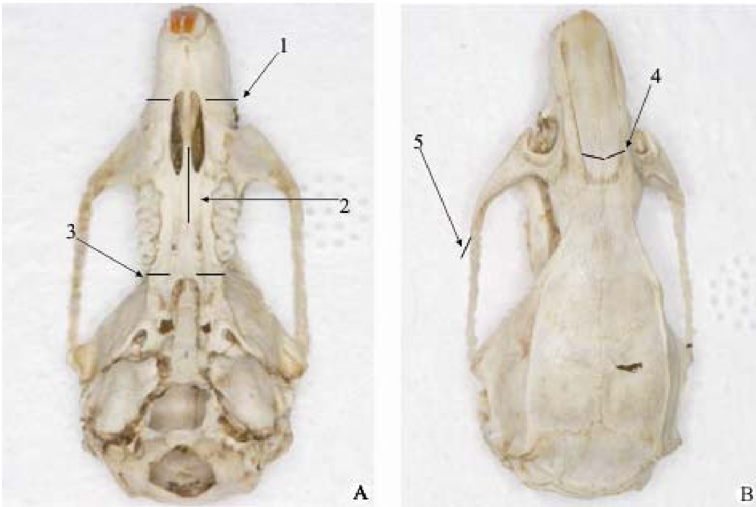

Fig. 2 Photographs of the examined circumaxillary sutures
A: from below; B: from above; 1: premaxillary suture; 2: midpalatal suture; 3: maxillopalatine suture; 4: frontonasal suture; 5: zygomaticotemporal suture

To quantify osteoclasts, 10 frozen sections from each specimen were stained for TRAP using a Sigma Diagnostic kit, and multinucleated TRAP positive cells were counted in all sections under high magnification.

1.5 Statistical Analysis

The results were expressed as $\bar{x}\pm s$. The differences of changes of anterior (inter-incisor distance) and posterior (inter-molar distance) arch width before and after ME were analyzed with paired *t*-test. Those differences between different experimental groups at different experimental stages were subjected to one-way analysis of variance (ANOVA). Cell counts were compared using the unpaired Student's *t*-test. Differences were considered significant at $P<0.05$.

2 RESULTS

2.1 Changes in Body Weight

Animals in the control group had steady weight gains during the experiment period. Experimental animals with either expander or alternate expander and constrictor used had temporary weight loss from the first to third day of activation but subsequently recovered. No statistically significant changes in body weight were observed between experiment and control animals.

2.2 Occlusal Radiographs and Cast Analysis

Radiographically, the midpalatal sutures were all split after 5 days of continuous expansion in both ME group and Alt-MEC group. After subsequent 5 days of constriction, the midpalatal suture of Alt-MEC group was closed as it was at the beginning of the experiment (fig. 3).

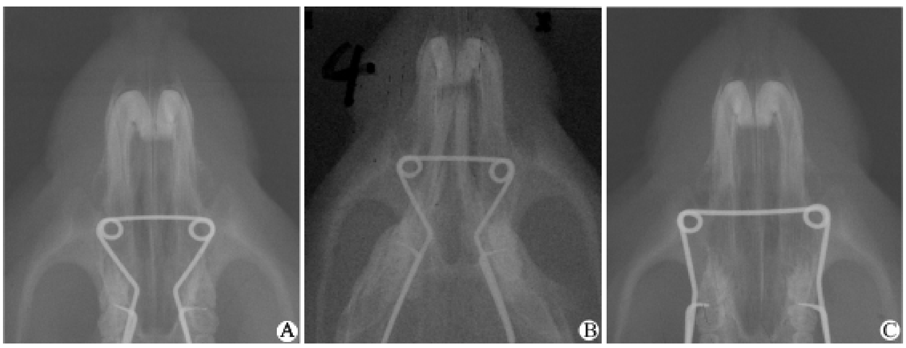

Fig. 3 Serial occlusal radiographs of the same animal in Alt-MEC group at different stages of the experiment
Mid-palatal suture was opened after first 5-day-expansion (B, T1) compared to control (A, T0) and closed after another 5-day-constriction (C, T2).

Inter-incisor and inter-molar measurements from the cast model showed that the dental arch was significantly expanded both anteriorly and posteriorly following application of expansion force in the two experiment groups. After 2.5 cycles of expansions and constrictions (T5), the distances between incisors and the first molars were significantly larger than those of ME group (T1) and 1.5 cycles of expansions and constriction (T3) (P<0.05, table 1). There was no significant arch width difference observed between before expansion (T0) and after once (T2) or twice (T4) constrictions (table 2).

Table 1 Comparisons of the inter-incisor and inter-molar distances (mm) before (T0) and after expansion (T1) in ME group and mean changes after 0.5 (T1), 1.5 (T3) and 2.5 cycles (T5) in Alt-MEC group

Variables	ME			Alt-MEC			*P* (ANOVA)		
	T0	T1	*P* (paired *t*-test)	T1–T0 (ΔE_1)	T3–T0 (ΔE_2)	T5–T0 (ΔE_3)	ΔE_1 *vs.* ΔE_2	ΔE_1 *vs.* ΔE_3	ΔE_2 *vs.* ΔE_3
Inter-incisor distance	1.89±0.01	2.10±0.02	0.012*	0.21±0.02	0.30±0.03	0.39±0.02	0.044*	0.036*	0.010*
Inter-molar distance	9.39±0.03	10.69±0.02	0.014*	1.30±0.01	1.42±0.02	1.54±0.02	0.038*	0.025*	0.016*

*P<0.05

Table 2 Comparisons of the inter-incisor and inter-molar distances (mm) before expansion (T0), after once (T2) and twice (T4) constriction in Alt-MEC group

Variables	T0	T2	T4	ANOVA
Inter-incisor distance	1.89±0.01	1.90±0.02	1.90±0.03	ns
Inter-molar distance	9.39±0.03	9.41±0.02	9.41±0.02	ns

ns: non-significant

2.3 Histological Analysis

The midpalatal suture consisted mainly of cartilage, i.e., two masses of chondrocytes covering the edges of palatal bones, separated from each other by a thin layer of fibrous tissue. The oral and nasal periosteal cell layers of the palatal bones were thicker in the region of the midpalatal suture. During the experimental period, the overall width of the midpalatal suture remained constant in control animals. In the experimental groups, the midpalatal suture was expanded and the collagen fibers were reoriented across the suture. At the same time, periosteal cells started to migrate into the suture. The suture was filled with spindle-shaped cells aligned in a direction parallel to the direction of mechanical force in the ME group, but the cells had no obvious directions in Alt-MEC group (fig. 4A). Osteoclasts were observed in both groups. However, obvious bone formation was mainly observed in Alt-MEC group. The width of the suture was expanded at a lager level with a cellular fibrous tissue filling the suture in Alt-MEC group. For maxillopalatine suture, no obvious changes were observed in ME group compared to control group. Only in some areas, collagen fibrils were extracted and osteoblasts increased in the edges (fig. 4B). In Alt-MEC group, collagen fibrils were distracted in multiple directions. In some areas osteoblasts were activated while osteoclasts were stimulated in other areas. No major differences were observed in premaxillary, zygomaticotemporal and frontonasal sutures between control and ME groups (fig. 4C, 4D and 4E). However, in Alt-MEC group, osteoblasts increased in multiple edges, with fibers extended and even detached from bone edges. There were also some compressed areas with positive osteoclasts.

No significance was observed on the counts of osteoclasts among sutures between control group and ME group except midpalatal suture (table 3). To the contrary, osteoclast counts in Alt-MEC group were all significantly higher in all sutures studied than those in control and ME groups (table 3). This result suggested in Alt-MEC group, bone reconstruction was more active than that in control and ME groups.

Table 3 Comparison of osteoclasts counts of the 5 circumaxillary sutures studied (cell number per area) in different groups (ANOVA)

Groups	Osteoclasts counts				
	Midpalatal suture	Palatomaxillary suture	Premaxillary suture	Zygomaticomaxillary suture	Frontomaxillary suture
Control	4.82±0.40	4.90±0.33	4.23±0.25	4.18±0.35	4.18±0.35
ME	5.93±0.28*	4.93±0.23	4.29±0.17	4.20±0.21	4.21±0.21
Alt-MEC	7.82±0.37*#	7.02±0.37*#	6.42±0.12*#	6.40±0.35*#	6.31±0.35*#

*P<0.05 *vs.* control group; #P<0.05 *vs.* ME group

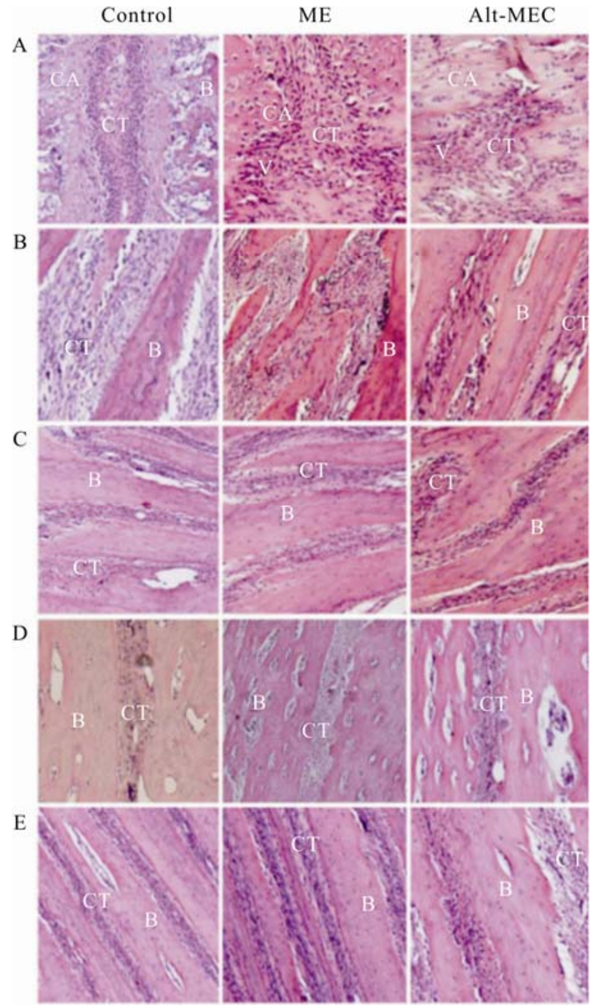

Fig. 4 Histological changes after ME and Alt-MEC in midpalatal (A), maxillopalatine (B), premaxillary (C), zygomaticotemporal (D), and frontonasal (E) sutures (HE, ×100)
Bones (B), connective tissues (CT), cartilage (CA) and vascular (V) are labeled in the pictures.

3 DISCUSSION

3.1 Arch Width Changes under Different Expansion Protocols

The effects of ME on maxillary complex have been extensively studied. A maxillary expander can widen the maxillary arch in the transverse direction, mainly by separating the maxillary halves, but also by moving the posterior teeth and alveolar process bucally[2, 37]. After ME, the amount of expansion followed a triangular pattern, with the greatest increase in maxillary arch width (intermolar or inter-premolar), followed by the maxillary width and the nasal width[19]. The greatest increase in dimensions was found at the molar crowns, which might be expected to represent the sum of skeletal and dentoalveolar changes. Molar tipping was also observed in nearly all subjects, confirming that changes of the dentoalveolar component was considerable[14, 38].

In our study, all animals in both experimental groups showed significant increase of the arch width not only in anterior (presented as inter-incisor distance) but also in posterior region (presented as inter-molar distance), with apparently larger increase in posterior region. This unequal increase suggested that different types of ME appliances may cause diverse skeletal changes and dentoalveolar modification, as reported by previous studies[7, 37]. Podesser *et al*[38] evaluated the effects of ME in growing children using computer tomography scanning and they raised doubts as to the efficiency of the Hyrax appliance and recommended further studies of alternative methods. Alternate maxillary expansions and constrictions introduced by Liou *et al*[26] is a new trial on this aspect. With repetitive alternate expansions and constrictions protocol, we noticed that as the cycles proceeded, the arch that was expanded became wider, even though it was restored after each constriction. According to the tooth extraction theory, this back and forth (lateral and medial) movement of the two maxillary halves makes the separation of the maxillary arch easier. But to what extent the arch width should be widened, what is the relationship among different types of ME appliances, the repetitive times of alternate expansions and constrictions and the maxillary expansion still warrant further studies.

3.2 Circumaxillary Sutures Response to Different Expansion Protocols

The maxilla articulates with other bones through cranial and circumaxillary sutures. Sutures in the skull have several functions. They unite bones, absorb forces, and act as joints that permit relative movement between bones. Even though the main objective of ME is to correct maxillary arch narrowness but its effects are not limited to the maxilla as it is associated with 10 bones in the face and head[13], thus ME may affect structures directly or indirectly related to the maxilla[12]. This involvement has been hypothesized following investigations based on histological methods, cast analysis[12], photoelastic models[39], bone scintigraphy[40], finite element analysis[10, 14, 41] and computed tomography (CT)[15, 16]. Several histological investigations have studied sutural responses to orthopedic forces in monkeys[42, 43], cats[44] and rats[35], and demonstrated a sign of increased cellular activity at suture level and immature bony tissue deposition along the suture borders[39,43]. In this study, significantly stretched collagen fiber running across the sutures was only seen in the midpalatal suture after ME and the immature bony tissue deposited along the borders of the suture. Other circumaxillary sutures studied had no obvious changes compared with the control except that collagen fibrils were extracted and osteoblasts increased only in some areas of maxillopalatine suture. This result suggested that cranial sutures respond differently to the external orthopedic forces according to their anantomic location and the degree of interdigitation. The histological effects of ME on circumaxillary sutures were mainly found on midpalatal suture.

Recently, CT studies[15, 16] have shown that force elicited by ME affects primarily sutures articulating directly to the maxilla (nasomaxillary, frontomaxillary and zygomaticomaxillary sutures) or the anterior sutures (intermaxillary and maxillary frontal nasal interfaces). These investigations supported those of the previous studies[10, 18, 19, 24, 25, 41, 43, 45] that reported the entire maxilla moved anteriorly and downwards in response to ME.

It was hypothesized that with repetitive Alt-MEC, the circumaxillary sutures will be extensively opened when compared with those after ME. Wang *et al*[33] demonstrated in a cat model by increasing the frequency of maxillary expansion through Alt-MEC for several times, circumaxillary sutures were separated and stretched to a greater degree than those in the ME group. In our study we found that Alt-MEC, compared with conventional ME, resulted in more active bone reconstructions in all sutures studied, characterized by significant osteoclast activity. Theoretically, the circumaxillary sutures that articulate directly to the maxilla are subjected more directly to expansions and constrictions of maxilla than the indirect-articulated circumaxillary sutures, and therefore should be reacted more actively, as concluded with Wang's study[33]. Due to the complex anatomic structure and orientation of the circumaxillary sutures, the direction and loading rate of force delivered vary differently among them[46]. The sutures running coronally might undertake tension and/or compression at the same time, thus even though they react actively in histological aspect, they may not present as widely opened. But when combined with maxillary protraction, the maxilla might be dramatically moved forward with more efficient remodeling produced by Alt-MEC.

To sum up, a rat animal model was established to evaluate the effect of ME and Alt-MEC on cranial and circumaxillary sutures. Most circumaxillary sutures studied showed significantly active response to Alt-MEC, while only midpalatal suture showed active reaction after ME.

Conflict of Interest Statement

The authors declare that there is no conflict of interest with any financial organization or corporation or individual that can inappropriately influence this work.

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(Received Jun. 24, 2014; revised Sep. 15, 2014)