Midfacial changes in the coronal plane induced by microimplant-supported skeletal expander, studied with cone-beam computed tomography images

Daniele Cantarella,[a] Ramon Dominguez-Mompell,[b] Christoph Moschik,[b] Sanjay M. Mallya,[c] Hsin Chuan Pan,[b] Mohammed R. Alkahtani,[a] Islam Elkenawy,[b] and Won Moon[b]
Los Angeles, Calif

Introduction: Our objectives were to evaluate midfacial skeletal changes in the coronal plane and the implications of circummaxillary sutures and to localize the center of rotation for the zygomaticomaxillary complex after therapy with a bone-anchored maxillary expander, using high-resolution cone-beam computed tomography. **Methods:** Fifteen subjects with a mean age of 17.2 ± 4.2 years were treated with a bone-anchored maxillary expander. Pretreatment and posttreatment cone-beam computed tomography images were superimposed and examined for comparison. **Results:** Upper interzygomatic distance increased by 0.5 mm, lower interzygomatic distance increased by 4.6 mm, frontozygomatic angles increased by 2.5° and 2.9° (right and left sides), maxillary inclinations increased by 2.0° and 2.5° (right and left sides), and intermolar distance increased by 8.3 mm (P <0.05). Changes in frontoethmoidal, zygomaticomaxillary, and molar basal bone angles were negligible (P >0.05). **Conclusions:** A significant lateral displacement of the zygomaticomaxillary complex occurred in late adolescent patients treated with a bone-anchored maxillary expander. The zygomatic bone tended to rotate outward along with the maxilla with a common center of rotation located near the superior aspect of the frontozygomatic suture. Dental tipping of the molars was negligible during treatment. (Am J Orthod Dentofacial Orthop 2018;154:337-45)

It is believed that during rapid palatal expansion (RPE), the main resistance to the opening of the midpalatal suture is probably not in the suture itself but, rather, in the surrounding structures with which the maxilla articulates, particularly the sphenoid and zygomatic bones.[1] Therefore, the expansion force might affect all circummaxillary sutures: internasal, nasomaxillary, frontomaxillary, frontonasal, frontozygomatic, zygomaticomaxillary, zygomaticotemporal, and pterygopalatine. This involvement has been hypothesized based on investigations that used histologic methods,[2] radiologic imaging,[3-5] photoelastic models,[6] bone scintigraphy,[7] and finite element methods.[8-12]

Cranial sutures respond differently to external orthopedic forces depending on their anatomic location and degree of interdigitation, and different studies have indicated diverse regions of the midfacial skeleton as the most affected by RPE. Some authors cited the frontozygomatic, zygomaticomaxillary, and zygomaticotemporal sutures as the primary anatomic sites of resistance to RPE.[13,14] Other clinical investigations have described greater changes in the sutures directly articulating with the maxilla than those indirectly articulatig.[4,15] Finite element method analyses found high stress levels in the zygomatic process of the maxilla, external walls of the orbit, frontozygomatic suture, and frontal process of the maxilla.[8-10]

From the School of Dentistry, Center for Health Science, University of California at Los Angeles.
[a]Division of Oral Biology and Medicine.
[b]Section of Orthodontics.
[c]Section of Oral and Maxillofacial Radiology.
All authors have completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest, and none were reported.
Address correspondence to: Won Moon and Daniele Cantarella, Division of Growth and Development, Section of Orthodontics, School of Dentistry, Center for Health Science, University of California, Los Angeles, Room 63-082 CHS, 10833 Le Conte Ave, Box 951668, Los Angeles, CA 90095-1668; e-mail, wmoon@dentistry.ucla.edu and danielecant@hotmail.com.
Submitted, September 2017; revised and accepted, November 2017.
0889-5406/$36.00

https://doi.org/10.1016/j.ajodo.2017.11.033

Fig 1. Method used to diagnose transverse maxillary skeletal deficiency. Measurement of **A,** maxillary and **B,** mandibular widths with a digital caliper; **C,** frontal view of the relationship between maxillary (*blue*) and mandibular (*red*) widths. In this patient, maxillary width is 55 mm, and mandibular width is 59.6 mm, for a maxillary transverse deficiency of 4.6 mm. Reprinted with permission from Cantarella D et al. Changes in the midpalatal and pterygopalatine sutures induced by micro-implant-supported skeletal expander, analyzed with a novel 3D method based on CBCT imaging. Prog Orthod 2017;18:34, Elsevier.

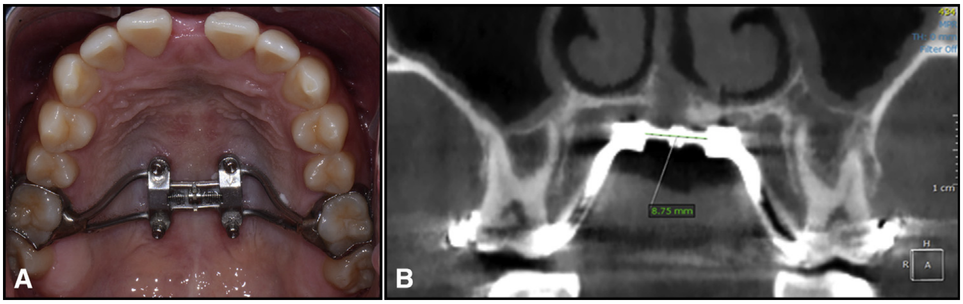

Fig 2. Maxillary skeletal expander: **A,** intraoral occlusal view; **B,** CBCT section showing the distance between the 2 halves of the expansion jackscrew after expansion on a patient. The opening of the midpalatal suture can also be appreciated. Reprinted with permission from Cantarella D et al. Changes in the midpalatal and pterygopalatine sutures induced by micro-implant-supported skeletal expander, analyzed with a novel 3D method based on CBCT imaging. Prog Orthod 2017;18:34, Elsevier.

For the rotational fulcrum of the maxillary bone during RPE, it is still being debated where it is located. Studies have established this center of rotation in different areas, frequently at the frontomaxillary suture.[9,10,16-20] Other authors have identified the center of rotation close to the superior orbital fissure.[2,11] In relation to the zygomatic bone, although high stress levels have been reported at the zygomatic sutures, no study has described its motion path during RPE and the location of its rotational fulcrum.[6,8,11,21]

Analysis of the circummaxillary suture modifications during rapid maxillary expansion have been previously conducted using study models,[22] 2-dimensional imaging,[16,19] and, more recently, 3-dimensional (3D) imaging based on computed tomographic data.[3-5,15,23] The introduction of cone-beam computed tomography (CBCT) and the development of new computer software allow obtaining multiplanar, 3D reconstructions, extending the possibilities for analysis of the craniofacial complex in living subjects.[24,25]

Miniscrews have been added to RPE devices, as proposed by Wilmes et al[26] in the hybrid hyrax appliance, to prevent buccal tipping of the lateral teeth and the negative consequences on their periodontal support. Furthermore, various miniscrew-assisted RPE appliances with different designs have been developed in recent years,[3,8,27-30] with the goal to enhance the orthopedic effects of maxillary expansion. A maxillary skeletal expander (MSE) is a specific type of bone-borne expander that uses 4 miniscrews in the posterior part of the palate with bicortical engagement.[3,31] The advantages of miniscrew-assisted RPE appliances over conventional expanders in achieving orthopedic changes are controversial in the literature. Comparisons between tooth-borne and bone-borne expanders have been published using CBCT technology, and different conclusions were drawn regarding the possibility for generating a greater orthopedic response with miniscrew-supported devices.[29,30] The aim of this investigation was to further evaluate the skeletal changes in the midface

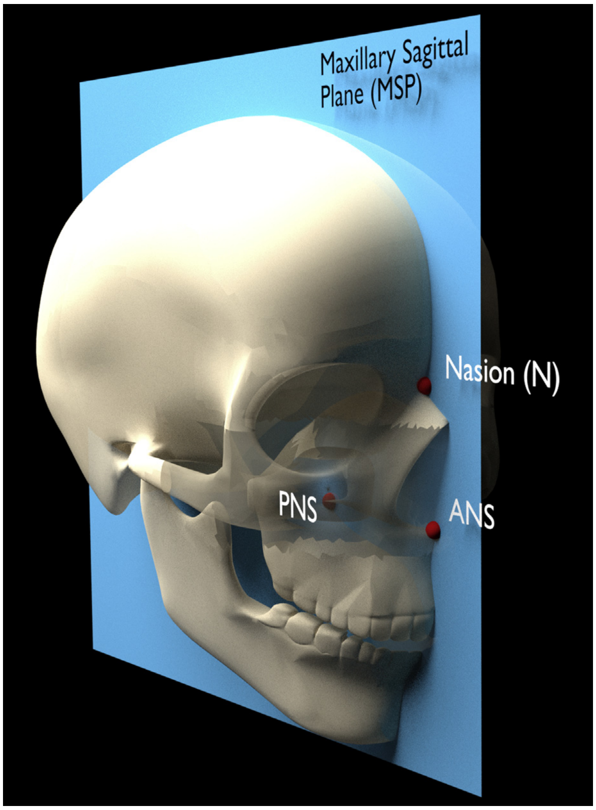

Fig 3. Illustration of the maxillary sagittal plane (MSP) passing through anterior nasal spine (*ANS*), posterior nasal spine (*PNS*), and nasion (*N*) on the preexpansion CBCT.

and the implications of circummaxillary sutures during rapid maxillary expansion with MSE, by describing the magnitude and pattern of lateral movement of the zygomaticomaxillary complex in the coronal plane, using high-resolution CBCT.

MATERIAL AND METHODS

Institutional Review Board approval from the University of California at Los Angeles was obtained for this retrospective study, which included 15 patients (6 male, 9 female), consecutively treated with MSE (Biomaterials Korea, Seoul, Korea), with a mean age of 17.2 ± 4.2 years (range, 13.9-26.2 years) of predominantly Hispanic ethnicity. Of the 15 patients, 9 had bilateral posterior crossbite, 5 had unilateral crossbite, and 1 was diagnosed with maxillary transverse deficiency without a dental crossbite. Treatment for all patients was done at the orthodontic clinic of the School of Dentistry at our university. Expansion with MSE was started and completed before bonding any brackets or other appliances.

The inclusion criteria were the following: (1) diagnosis of a transverse maxillary deficiency based on a modified version of Andrews' analysis[32] of 6 elements, as elaborated below; (2) treatment with MSE as part of the overall treatment plan, (3) CBCT scans taken at 2 times: before treatment and within 3 weeks after active expansion; (4) no craniofacial abnormalities, and (5) no previous orthodontic treatment.

The method adopted to analyze the relationship between the maxillary and mandibular widths is described in Figure 1. Maxillary width is represented by the distance between the right and left most concave points lying on the maxillary vestibule at the level of the mesiobuccal cusp of the first molars. Mandibular width is defined as the distance between the right and left WALA ridges located at the level of the mesiobuccal groove of the first molars.[32] To assess transverse deficiency, we calculated the difference between the mandibular and maxillary widths, which ideally should have been equal. It also gave an estimate of the amount of maxillary skeletal expansion required (Fig 1).

MSE was chosen instead of a traditional tooth-borne expander, based on the following criteria: patient maturity (appearance of secondary sexual characteristics including facial hair, voice changes, onset of menstruation, and cervical vertebral maturation stage higher than CS4),[33] dolichofacial vertical pattern (based on high SN-GoGn and FMA angles), and positive history of nasal airway problems. At our Section of Orthodontics, dolichofacial patients are treated with MSE rather than tooth-borne expanders, because bone-borne appliances tend to yield less posterior mandibular rotation.[8]

An MSE appliance (Fig 2, *A*) consists of a jackscrew unit supported by 4 palatal microimplants and attached to the molars with connecting arms and molar bands.[3] The rate of expansion was 2 turns per day (0.25 mm per turn) until a diastema appeared; then the rate changed to 1 turn per day. Expansion was stopped when the maxillary skeletal width, defined in Figure 1, was equal to or greater than the mandibular width. After completion, the MSE was kept in place without further activation for at least 3 months to retain the expansion.

The amount of activation of the MSE jackscrew applied to the patients was calculated as follows: the distance between the 2 halves of the expansion screw was measured on the CBCT image taken after expansion (Fig 2, *B*); the preexpansion distance was determined by taking a CBCT scan on an MSE appliance and measuring the distance 10 times. The preexpansion distance was subtracted from the postexpansion one, and the values were then averaged to obtain the mean and standard deviation.

The CBCT scans were taken at 2 times: before expansion and within 3 weeks after active expansion. The time

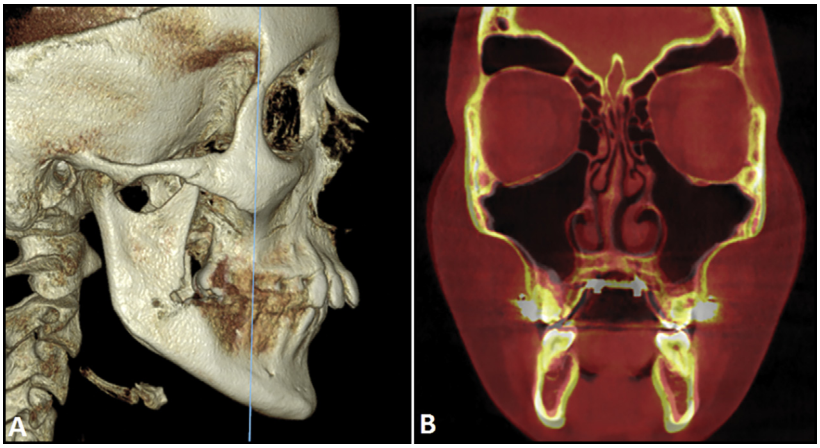

Fig 4. Coronal zygomatic section: **A,** lateral view of 3D rendering, showing the coronal zygomatic section in *blue*; **B,** pretreatment and posttreatment superimposed image of a MSE patient.

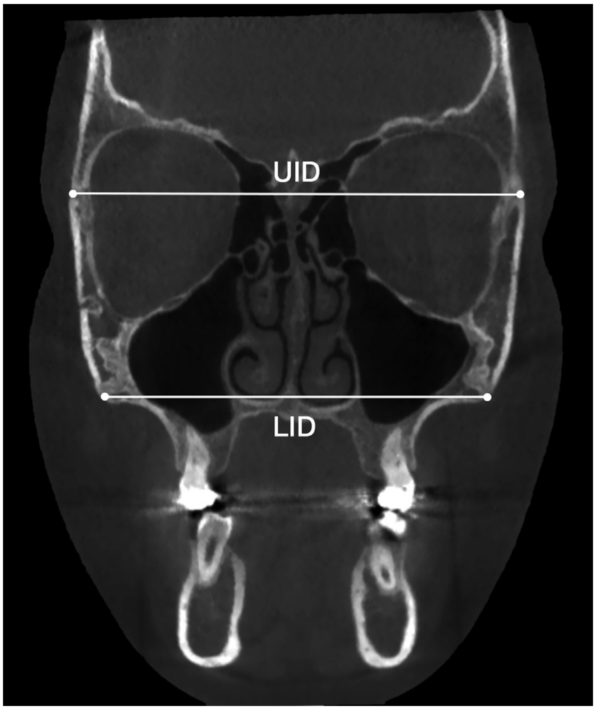

Fig 5. Skeletal linear measurements in the coronal zygomatic section: upper interzygomatic distance (*UID*) and lower interzygomatic distance (*LID*).

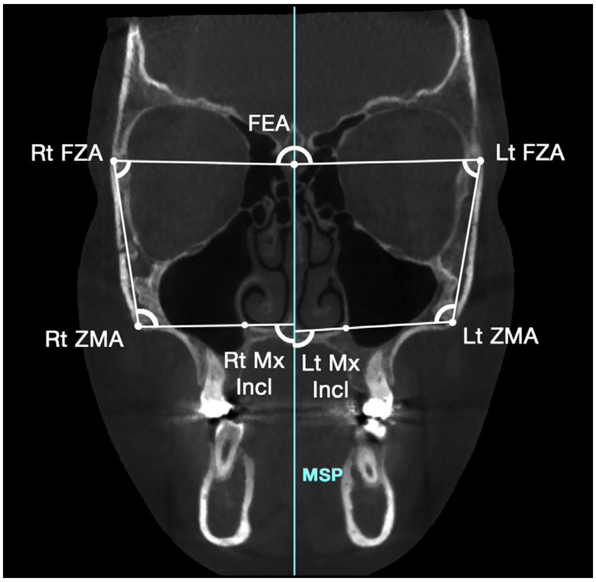

Fig 6. Skeletal angular measurements in the coronal zygomatic section: frontoethmoidal angle (*FEA*), frontozygomatic angle (*FZA*), zygomaticomaxillary angle (*ZMA*), and maxillary inclination (*Mx Incl*). *Rt*, Right; *Lt*, left; *MSP*, maxillary sagittal plane.

between the scans was 5 ± 2 months, and this included the time for administrative procedures between the patient and the clinic's office, as well as for appliance fabrication and delivery. Postexpansion scans were taken before the patient received any bonded brackets or other appliances, to analyze skeletal changes induced solely by MSE.

A scanner (5G; NewTom, Verona, Italy) was used for all patients, with an 18 × 16 cm field of view, 14-bit gray scale, and a standard voxel size of 0.3 mm. Configuration of the CBCT included scan time of 18 seconds (3.6 seconds emission time), with 110 kV. We used an automated exposure control system to detect the patient's anatomic density and adjust the milliamperes accordingly.

OnDemand3D (Cybermed, Daejeon, Korea) is a software capable of superimposing the preexpansion and

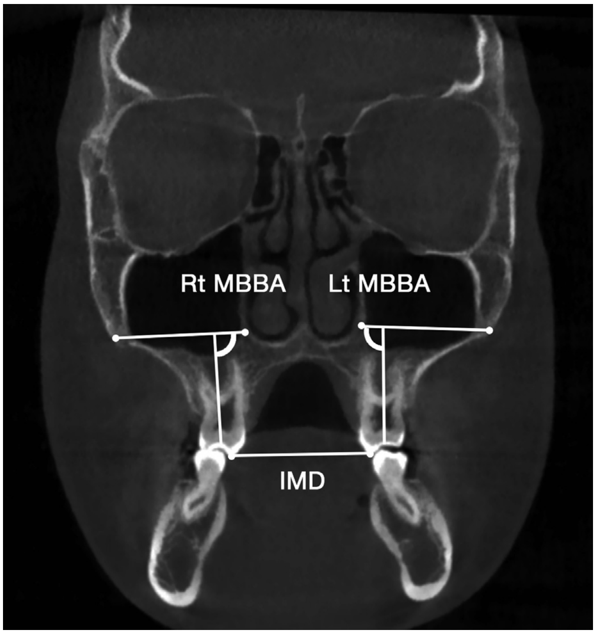

Fig 7. Dental analysis in the coronal molar section (*CMS*): intermolar distance (*IMD*) and molar basal bone angle (*MBBA*). *Rt*, Right; *Lt*, left.

postexpansion CBCT images of the patient using the anatomic structures of the entire anterior cranial base in adults[24] and the anterior cranial fossae in growing children,[25] by automated processing in matching the voxel gray-scale patterns. Accuracy of the superimposition method has been recently validated.[34] After superimposition of CBCT data sets, the following novel methodology was used to evaluate the skeletal changes in the midface. The maxillary sagittal plane was identified,[35] passing through the anterior nasal spine, posterior nasal spine, and nasion on the preexpansion CBCT image (Fig 3). Then the coronal zygomatic section (Fig 4) was selected to evaluate the changes in the maxillary, zygomatic, frontal, and ethmoid bones. The section passes through the lowest point of the zygomaticomaxillary sutures and the uppermost point of the frontozygomatic sutures. In this coronal section, both linear and angular skeletal measurements were made (Figs 5 and 6).

Skeletal linear measurements included the upper interzygomatic distance that extends from the most external point of the right frontozygomatic suture to the most external point of the left frontozygomatic suture, and the lower interzygomatic distance that extends from the most external point of the right zygomaticomaxillary suture to the most external point of the left zygomaticomaxillary suture (Fig 5).

Skeletal angular measurements included the frontoethmoidal angle, frontozygomatic angle, zygomaticomaxillary angle, and maxillary inclination, as shown in Figure 6.

Table I. Parameters evaluated in the study

Skeletal linear measurements	
1	Upper interzygomatic distance
2	Lower interzygomatic distance
Skeletal angular measurements	
3	Frontoethmoidal angle
4	Right frontozygomatic angle
5	Left frontozygomatic angle
6	Right zygomaticomaxillary angle
7	Left zygomaticomaxillary angle
8	Right maxillary inclination
9	Left maxillary inclination
Dental measurements	
10	Intermolar distance
11	Right molar basal bone angle
12	Left molar basal bone angle

The frontoethmoidal angle is formed by the lowest point of crista galli of the ethmoid bone and the most external points of the frontozygomatic sutures bilaterally. The frontozygomatic angle is formed by the lowest point of crista galli, the most external point of the frontozygomatic suture, and the most external point of the zygomaticomaxillary suture. The zygomaticomaxillary angle is formed by the same landmarks as above, located at the frontozygomatic and zygomaticomaxillary sutures, and by the point where the cortical bones of the maxillary sinus floor and the nasal floor merge. Maxillary inclination is the angle between 2 lines: one that connects the most lateral point of the maxillary bone and the point where the cortical bones that form the floor of the nasal cavity and maxillary sinus merge, and the other line represented by the maxillary sagittal plane.

For the dental analysis, a coronal section through the furcation of the roots and the central fossae of the maxillary first molars was used, called the coronal molar section (Fig 7).

Dental measurements included the intermolar distance and the molar basal bone angle. The intermolar distance is measured at the level of the most occlusal point of the mesiopalatal cusp of the maxillary first molars, and the molar basal bone angle is the angle formed by the same horizontally oriented line used in maxillary inclination and the line connecting the central pit of the molar crown to the furcation of the roots.

All evaluated parameters are listed in Table I.

Statistical analysis

For each variable, the preexpansion value was subtracted from the postexpansion value. The mean

Table II. Skeletal and dental measurements

	Unit	Before expansion		After expansion		Treatment change		P value
		Mean	SD	Mean	SD	Mean	SD	
Skeletal linear measurements								
1 Upper interzygomatic distance	mm	98.18	2.93	98.70	3.09	0.52	0.37	<0.0001*
2 Lower interzygomatic distance	mm	86.14	4.88	90.76	5.66	4.62	1.33	<0.0001*
Skeletal angular measurements								
3 Frontoethmoidal angle	°	169.71	6.51	169.53	6.52	-0.18	0.43	0.441
4 Right frontozygomatic angle	°	79.36	4.09	81.81	3.81	2.45	1.26	<0.0001*
5 Left frontozygomatic angle	°	77.94	2.64	80.85	2.79	2.91	1.39	<0.0001*
6 Right zygomaticomaxillary angle	°	103.80	5.52	103.50	5.68	-0.23	0.88	0.324
7 Left zygomaticomaxillary angle	°	105.80	5.51	105.50	5.29	-0.35	0.96	0.175
8 Right maxillary inclination	°	96.61	4.85	98.63	5.31	2.01	1.03	<0.0001*
9 Left maxillary inclination	°	97.25	4.42	99.74	4.64	2.49	1.81	0.000*
Dental measurements								
10 Intermolar distance	mm	38.58	3.53	46.91	3.46	8.33	2.29	<0.0001*
11 Right molar basal bone angle	°	89.79	8.36	91.83	10.24	2.04	3.31	0.076
12 Left molar basal bone angle	°	90.33	8.45	92.15	11.50	1.83	4.26	0.144

*P <0.01.

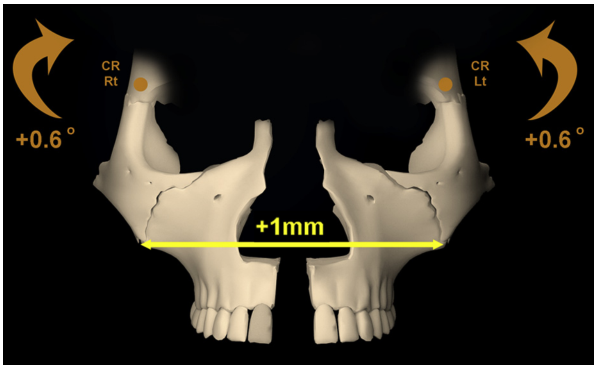

Fig 8. Pattern of lateral movement of the zygomaticomaxillary complex. For each millimeter of increase in lower interzygomatic distance, each zygomaticomaxillary half rotates 0.6°. *CR*, Center of rotation; *Rt*, right; *Lt*, left.

change was compared with zero, and the P value was computed using the Wilcoxon signed rank test for paired data.

For the assessment of method reliability, measurements were obtained for all 12 variables on 8 randomly selected patients by 2 raters. Measurements were then repeated after 2 weeks by the same operators, after reorienting the skull according to the reference planes to compute reliability parameters that are the combination of error in identification of reference planes (coronal zygomatic section, maxillary sagittal plane, coronal molar section) and error in landmark localization. The calculated parameters were rater standard deviation, rater coefficient of variation, error standard deviation, error coefficient of variation, and intraclass correlation coefficient.

RESULTS

The average amount of activation of the MSE expansion jackscrew was 6.8 ± 1.9 mm (range, 4.1-10.5 mm). The duration of maxillary expansion ranged from 12 to 36 days.

For the skeletal linear measurements, both upper interzygomatic distance and lower interzygomatic distance significantly increased (Table II).

In the skeletal angular measurements, the largest change was at the frontozygomatic angle, followed by the maxillary inclination (P <0.05), whereas modifications at the frontoethmoidal and zygomaticomaxillary angles were not significant (P >0.05).

The pattern of lateral displacement of the zygomaticomaxillary complex within the craniofacial complex was also calculated as the ratio between the increase in frontozygomatic angle (average of right and left sides) and the increase in the lower interzygomatic distance. The ratio was 0.6° per millimeter (2.68°/4.62 mm) (Fig 8).

Regarding dental measurements, molar inclination relative to the maxillary bone, obtained from the molar basal bone angle showed no significant changes with MSE therapy (P >0.05), whereas intermolar distance significantly increased, as shown in Table II.

For the considered parameters, the rater coefficient of variation was 1.36% or less, and the error coefficient of variation was 1.75% or less (Table III), showing that measurements were highly reliable.

Table III. Analysis of method reliability

Parameter	Unit	Rater SD	Error SD	Rater CV	Error CV	ICC
Skeletal linear measurements						
1 Upper interzygomatic distance	mm	0.17	0.22	0.17%	0.22%	99.5%
2 Lower interzygomatic distance	mm	0.00	0.39	0.00%	0.45%	99.3%
Skeletal angular measurements						
3 Frontoethmoidal angle	°	0.84	1.24	0.50%	0.75%	92.5%
4 Right frontozygomatic angle	°	0.31	0.55	0.41%	0.72%	92.0%
5 Left frontozygomatic angle	°	1.01	1.06	1.35%	1.42%	83.8%
6 Right zygomaticomaxillary angle	°	0.00	0.76	0.00%	0.75%	99.0%
7 Left zygomaticomaxillary angle	°	1.40	0.90	1.36%	0.88%	94.6%
8 Right maxillary inclination	°	0.00	1.42	0.00%	1.53%	97.0%
9 Left maxillary inclination	°	0.49	0.58	0.53%	0.63%	99.3%
Dental measurements						
10 Intermolar distance	mm	0.20	0.34	0.53%	0.92%	99.1%
11 Right molar basal bone angle	°	0.42	1.36	0.45%	1.48%	97.4%
12 Left molar basal bone angle	°	0.00	1.47	0.00%	1.75%	96.7%

SD, Dahlberg standard deviation[36]; *Rater CV*, rater coefficient of variation = rater SD/overall mean; *Error CV*, error coefficient of variation = error SD/overall mean; *ICC*, intraclass correlation coefficient = patient variance/total variance.

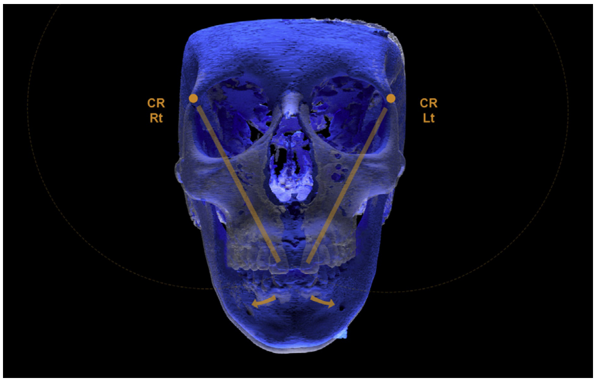

Fig 9. Superimposed 3D model of an MSE patient showing the rotation of the zygomaticomaxillary complex with a center of rotation (CR) located slightly above the superior aspect of the frontozygomatic suture. Opening of the frontomaxillary and nasomaxillary sutures can also be seen. *Blue*, Preexpansion; *white*, postexpansion; *Rt*, right; *Lt*, left.

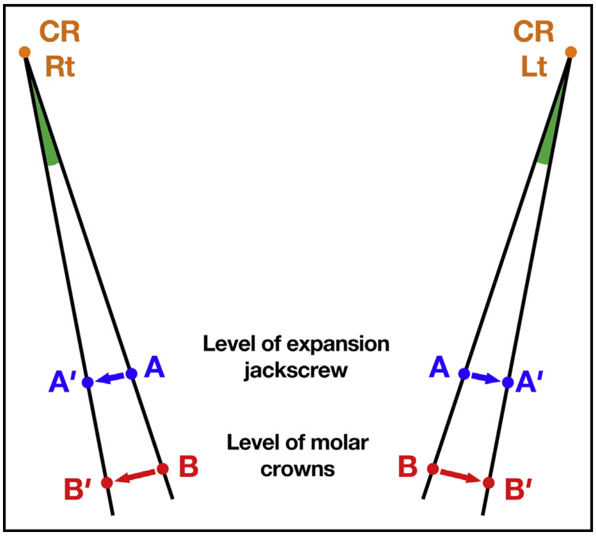

Fig 10. Schematic illustration showing that, for the same amount of angular rotation, points closer to the center of rotation (*A-point*) undergo a shorter linear displacement than points farther from the center of rotation (*B-point*). *CR Rt*, Center of rotation for the right zygomaticomaxillary complex; *CR Lt*, center of rotation for the left zygomaticomaxillary complex.

DISCUSSION

Previous studies have consistently found that circummaxillary sutures' resistance leads to a triangular separation pattern of expansion in the coronal plane, with the apex toward the nasal cavity and the base at the level of the palatine processes.[9,16-20]

In this study, the larger augmentation in lower interzygomatic distance (+4.6 mm), when compared with the upper interzygomatic distance (+0.5 mm), shows outward rotation of the zygomatic bone with greater movement in its lower part than the upper part. This rotational movement is confirmed by the increases in the frontozygomatic angle of 2.5° and 2.9° for the right and left sides, respectively. Conversely, the frontoethmoidal angle showed negligible changes, demonstrating that ethmoid and frontal bones did not change their relative positions during maxillary expansion.

The zygomaticomaxillary angle shows the relative inclination between the maxillary and zygomatic bones.

Its change was negligible and without statistical significance, demonstrating that the relationship between the maxillary basal bone and the zygomatic bone was maintained during the expansion and that they rotate together around a common center of rotation.

Since the increase in upper interzygomatic distance was negligible, and the increases in lower interzygomatic distance and frontozygomatic angle were considerable, we concluded that the zygomaticomaxillary complex rotates outward with a center of rotation located near the frontozygomatic suture (Fig 9). In the literature, the rotational fulcrum location of the maxilla during expansion has been debated. Most finite element method studies affirm that the fulcrum is located at the frontomaxillary suture.[9,10,20] However, Gardner and Kronman,[2] in a study with rhesus monkeys, and Gautam et al,[11] in a finite element method investigation, found that the center of rotation for the maxilla is close to the superior orbital fissure. The data we obtained indicate that the fulcrum may be located more laterally than the previous findings, since the center of rotation for the zygomaticomaxillary complex was slightly above the superior aspect of the frontozygomatic suture. Maxillary rotation around this fulcrum area during expansion could explain the downward movements of anterior nasal spine and posterior nasal spine induced by expanders, reported by several authors.[11,15,19] The maxilla is located medially and inferiorly relative to this fulcrum. As the zygomaticomaxillary complex rotates outward around the frontozygomatic suture area, a half maxilla initially moves downward and outward (Fig 9). The opening of the frontomaxillary and nasomaxillary sutures, frequently found in MSE patients (Fig 9) and reported in several studies[4,11,15] could also be explained by this rotational movement. If the frontomaxillary suture area was the fulcrum during expansion, the opening of the frontomaxillary and nasomaxillary sutures would be severely limited.

Clinical studies have indicated that tooth-borne expanders generate negligible or very small lateral displacements of the zygomatic bone. Baccetti et al[37] reported that the Haas appliance produces increases in bizygomatic width of 0.4 and 0.3 mm in early treated patients and late adolescent patients, respectively. Ong et al[38] found a transverse expansion of the zygomatic bones of 1.4 mm with a cast cap splint expander used in adolescents.

Conversely, in our study, the lower interzygomatic distance increased by an average of 4.6 mm. The lateral displacement of the zygomatic bones with MSE was substantially greater than what has been reported for tooth-borne palatal expanders, probably due to the different force delivery involved in the 2 types of appliances. With tooth-borne expanders, part of the jackscrew activation is dissipated in buccal dentoalveolar tipping of supporting teeth,[39] whereas with MSE the force is directly transmitted to the maxilla, generating a pressure capable of laterally displacing the zygomatic bone. The buccal tipping of the molars, analyzed with the molar basal bone angle, was negligible and without statistical significance. As the zygomatic bone is pushed laterally by the underlying maxilla, it tends to rotate around the weaker frontozygomatic suture, generating an increase in the frontozygomatic angle. This significant displacement of the zygomatic bone indicates that a larger midfacial orthopedic response can be achieved with MSE.

The movement of the maxillary and zygomatic bones is rotational. The pattern of lateral movement of the zygomaticomaxillary complex was calculated as a ratio between the increase in the frontozygomatic angle and the increase in lower interzygomatic distance. For a 1-mm increase in lower interzygomatic distance, the zygomaticomaxillary complex rotated 0.6° (Fig 8).

This rotational movement can explain the discrepancy in intermolar distance augmentation (+8.3 mm) vs the amount of jackscrew activation (+6.8 mm). Since the change in molar inclination relative to the maxillary basal bone was negligible, the larger movement of molar crowns compared with the jackscrew activation (1.5 mm difference) can be due to the rotational movement of the zygomaticomaxillary complex. For the same amount of angular rotation, points farther from the rotational fulcrum (ie, molar crowns) undergo greater linear movements than points closer to the fulcrum (ie, the 2 halves of the expansion jackscrew), as shown in Figure 10.

One limitation of our investigation was its retrospective nature. Further prospective studies with patients of different ethnicities and diverse skeletal patterns would be beneficial to define how skull morphology can affect the biomechanical response to the orthopedic forces of the MSE.

CONCLUSIONS

1. MSE efficiently generated midfacial expansion in late adolescent patients.
2. The zygomatic bone was significantly displaced in a lateral direction during miniscrew-assisted maxillary expansion.
3. In the coronal plane, the center of rotation for the zygomaticomaxillary complex was located slightly above the superior aspect of the frontozygomatic suture.
4. Dental tipping of the molars was negligible during treatment.

REFERENCES

1. Isaacson RJ, Wood JL, Ingram AH. Forces produced by rapid maxillary expansion. Part I. Design of the force measuring system. Angle Orthod 1964;34:256-60.
2. Gardner GE, Kronman JH. Cranioskeletal displacements caused by rapid palatal expansion in the rhesus monkey. Am J Orthod 1971; 59:146-55.
3. Carlson C, Sung J, McComb RW, Machado AW, Moon W. Microimplant-assisted rapid palatal expansion appliance to orthopedically correct transverse maxillary deficiency in an adult. Am J Orthod Dentofacial Orthop 2016;149:716-28.
4. Leonardi R, Sicurezza E, Cutrera A, Barbato E. Early post-treatment changes of circumaxillary sutures in young patients treated with rapid maxillary expansion. Angle Orthod 2011;81:36-41.
5. Ghoneima A, Abdel-Fattah E, Hartsfield J, El-Bedwehi A, Kamel A, Kula K. Effects of rapid maxillary expansion on the cranial and circummaxillary sutures. Am J Orthod Dentofacial Orthop 2011;140: 510-9.
6. Shetty V, Caridad JM, Caputo AA, Chaconas SJ. Biomechanical rationale for surgical-orthodontic expansion of the adult maxilla. J Oral Maxillofac Surg 1994;52:742-9.
7. Baydas B, Yavuz I, Uslu H, Dagsuyu IM, Ceylan I. Nonsurgical rapid maxillary expansion effects on craniofacial structures in young adult females. A bone scintigraphy study. Angle Orthod 2006;76:759-67.
8. MacGinnis M, Chu H, Youssef G, Wu KW, Machado AW, Moon W. The effects of micro-implant assisted rapid palatal expansion (MARPE) on the nasomaxillary complex—a finite element method (FEM) analysis. Prog Orthod 2014;15:52.
9. Jafari A, Shetty KS, Kumar M. Study of stress distribution and displacement of various craniofacial structures following application of transverse orthopedic forces—a three-dimensional FEM study. Angle Orthod 2003;73:12-20.
10. Işeri H, Tekkaya AE, Oztan O, Bilgiç S. Biomechanical effects of rapid maxillary expansion on the craniofacial skeleton, studied by the finite element method. Eur J Orthod 1998;20:347-56.
11. Gautam P, Valiathan A, Adhikari R. Stress and displacement patterns in the craniofacial skeleton with rapid maxillary expansion: a finite element method study. Am J Orthod Dentofacial Orthop 2007;132:1-11.
12. Ludwig B, Baumgaertel S, Zorkun B, Bonitz L, Glasl B, Wilmes B, et al. Application of a new viscoelastic finite element method model and analysis of miniscrew-supported hybrid hyrax treatment. Am J Orthod Dentofacial Orthop 2013;143:426-35.
13. Bell WH, Epker BN. Surgical-orthodontic expansion of the maxilla. Am J Orthod 1976;70:517-28.
14. Lines PA. Adult rapid maxillary expansion with corticotomy. Am J Orthod 1975;67:44-56.
15. Garib DG, Henriques JF, Janson G, Freitas MR, Coelho RA. Rapid maxillary expansion—tooth tissue-borne versus tooth-borne expanders: a computed tomography evaluation of dentoskeletal effects. Angle Orthod 2005;75:548-57.
16. Haas AJ. The treatment of maxillary deficiency by opening of the midpalatal suture. Angle Orthod 1965;35:200-17.
17. Haas AJ. Palatal expansion: just the beginning of dentofacial orthopedics. Am J Orthod 1970;57:219-55.
18. Wertz RA. Skeletal and dental changes accompanying rapid midpalatal suture opening. Am J Orthod 1970;58:41-66.
19. Wertz R, Dreskin M. Midpalatal suture opening: a normative study. Am J Orthod 1977;71:367-81.
20. Braun S, Bottrel JA, Lee KG, Lunazzi JJ, Legan H. The biomechanics of rapid maxillary sutural expansion. Am J Orthod Dentofacial Orthop 2000;118:257-61.
21. Sun Z, Hueni S, Tee BC, Kim H. Mechanical strain at alveolar bone and circummaxillary sutures during acute rapid palatal expansion. Am J Orthod Dentofacial Orthop 2011;139:219-28.
22. Timms DJ. A study of basal movement with rapid maxillary expansion. Am J Orthod 1980;77:500-7.
23. Garrett BJ, Caruso JM, Rungcharassaeng K, Farrage JR, Kim JS, Taylor GD. Skeletal effects to the maxilla after rapid maxillary expansion assessed with cone-beam computed tomography. Am J Orthod Dentofacial Orthop 2008;134:8-9.
24. Cevidanes LH, Bailey LT, Tucker GR Jr, Styner MA, Mol A, Phillips CL, et al. Superimposition of 3D cone-beam CT models of orthognathic surgery patients. Dentomaxillofac Radiol 2005;34:369-75.
25. Cevidanes LH, Heymann G, Cornelis MA, DeClerck HJ, Tulloch JF. Superimposition of 3-dimensional cone-beam computed tomography models of growing patients. Am J Orthod Dentofacial Orthop 2009;136:94-9.
26. Wilmes B, Nienkemper M, Drescher D. Application and effectiveness of a mini-implant and tooth-borne rapid palatal expansion device: the hybrid hyrax. World J Orthod 2010;11:323-30.
27. Park JJ, Park YC, Lee KJ, Cha JY, Tahk JH, Choi YJ. Skeletal and dentoalveolar changes after miniscrew-assisted rapid palatal expansion in young adults: a cone beam computed tomography study. Korean J Orthod 2017;47:77-86.
28. Maino BG, Paoletto E, Lombardo L, Siciliani G. From planning to delivery of a bone-borne rapid maxillary expander in one visit. J Clin Orhod 2017;51:198-207.
29. Lagravère MO, Carey J, Heo G, Toogood RW, Major PW. Transverse, vertical, and anteroposterior changes from bone-anchored maxillary expansion vs traditional rapid maxillary expansion: a randomized clinical trial. Am J Orthod Dentofacial Orthop 2010;137:304-12.
30. Lin L, Ahn HW, Kim SJ, Moon SC, Kim SH, Nelson G. Tooth-borne vs bone-borne rapid maxillary expanders in late adolescence. Angle Orthod 2015;85:253-62.
31. Lee RJ, Moon W, Hong C. Effects of monocortical and bicortical mini-implant anchorage on bone-borne palatal expansion using finite element analysis. Am J Orthod Dentofacial Orthop 2017; 151:887-97.
32. Andrews LF, Andrews WA. The six elements of orofacial harmony. Andrews J Orthod Orofac Harmony 2000;1:13-22.
33. Baccetti T, Franchi L, McNamara JA Jr. The cervical vertebral maturation (CVM) method for the assessment of optimal treatment timing in dentofacial orthopedics. Semin Orthod 2005;11:119-29.
34. Weissheimer A, Menezes LM, Koerich L, Pham J, Cevidanes LH. Fast three-dimensional superimposition of cone beam computed tomography for orthopaedics and orthognathic surgery evaluation. Int J Oral Maxillofac Surg 2015;44:1188-96.
35. Cantarella D, Dominguez-Mompell R, Mallya SM, Moschik C, Pan HC, Miller J, et al. Changes in the midpalatal and pterygopalatine sutures induced by micro-implant-supported skeletal expander, analyzed with a novel 3D method based on CBCT imaging. Prog Orthod 2017;18:34.
36. Dahlberg G. Statistical methods for medical and biological students. New York: Interscience Publications; 1940.
37. Baccetti T, Franchi L, Cameron CG, McNamara JA Jr. Treatment timing for rapid maxillary expansion. Angle Orthod 2001;71:343-50.
38. Ong SC, Khambay BS, McDonald JP, Cross DL, Brocklebank LM, Ju X. The novel use of three-dimensional surface models to quantify and visualise the immediate changes of the mid-facial skeleton following rapid maxillary expansion. Surgeon 2015;13:132-8.
39. Weissheimer A, de Menez LM, Mezomo M, Dias DM, de Lima EMS, Rizzatto SM. Immediate effects of rapid maxillary expansion with Haas-type and hyrax-type expanders: a randomized clinical trial. Am J Orthod Dentofacial Orthop 2011;140:366-76.