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AJO-DO

Three-dimensional computed tomography analysis of airway volume changes after rapid maxillary expansion

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Introduction: In this retrospective study with 3-dimensional computed tomography, we evaluated airway volume, soft-palate area, and soft-tissue thickness changes before and after rapid maxillary expansion in adolescents. Another purpose was to determine whether rapid maxillary expansion caused changes in the palatal and mandibular planes and facial height. **Methods:** The sample comprised 20 patients who were treated with rapid maxillary expansion. Spiral tomographs were taken before and 3 months after treatment. Reliability studies were performed, and then volumetric, soft-palate area, soft-tissue thickness, and cephalometric parameters were compared on the tomographs. Intraclass correlations were performed on the reliability measurements. Before and after rapid maxillary expansion measurements were compared by using Wilcoxon signed rank tests. Spearman correlation coefficients were used to evaluate the associations among the airway volume, soft-palate area, soft-tissue thickness, and cephalometric measurements. Significance was accepted at $P \leq 0.05$ for all tests. **Results:** Intraclass correlation coefficients were ≥ 0.90 for all reliability measures. Significant increases from before to after rapid maxillary expansion were found in nasal cavity and nasopharynx volumes, and for the measurements of MP-SN, S-PNS, N-ANS, ANS-Me, and N-Me. Significant positive correlations existed between changes in PP-SN and N-ANS, and ANS-Me and N-Me. **Conclusions:** Rapid maxillary expansion causes significant increases in nasal cavity volume, nasopharynx volume, anterior and posterior facial heights, and palatal and mandibular planes. (Am J Orthod Dentofacial Orthop 2012;141:618-26)

Rapid maxillary expansion (RME) is an orthodontic and orthopedic treatment option to correct posterior crossbites and maxillary transverse deficiencies. Rigid, fixed RME appliances produce heavy forces that result in skeletal or orthopedic expansion and also dentoalveolar changes.[1] When the maxillary dental arch is rapidly expanded, the maxillary and palatine bones disarticulate along the midpalatal suture, and there are also changes to the frontomaxillary, zygomaticomaxillary, zygomaticotemporal, and pterygopalatine sutures.[1,2] Stress distribution and displacement pattern studies have evaluated the effects of RME on the craniofacial complex.[1] A finite element analysis showed minimum displacement of the pterygoid plates near the cranial base and maximum displacement in the areas of the maxillary central incisors and the anteroinferior border of the nasal septum.[1] Jafari et al[1] also demonstrated that the lateral structures of the nasomaxillary complex moved upward, and midline structures, including ANS and A-point, moved downward. Garrett et al[3] confirmed clinically that midpalatal sutural separation occurred in a triangular pattern with the wider base in the anterior part of the maxilla, and the effects of RME extended to the surrounding nasal and craniofacial structures.

According to Moss's functional matrix theory, during breathing, a continuous flow of air through the nasal

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Table I. Definitions of anatomic areas

	Anterior boundary	*Posterior boundary*	*Superior boundary*	*Inferior boundary*
Nasal cavity	Line connecting the anterior nasal spine (ANS) to the tip of the nasal bone to nasion (N)	Line extending from sella (S) to the posterior nasal spine (PNS)	Line connecting N to S	Line extending from the ANS to the PNS
Nasopharynx	Line extending from sella (S) to the posterior nasal spine (PNS)	Line extending from S to the tip of the odontoid process		Line extending from the PNS to tip of the odontoid process
Oropharynx	Line extending from the posterior nasal spine (PNS) to the base of the epiglottis	Line extending from the tip of the odontoid process to the posterior-superior border of CV 4	Line extending from the PNS to the tip of the odontoid process	Line extending from the base of the epiglottis to the posterior-superior border of CV 4
Hypopharynx	Line extending from the base of the epiglottis to the inferior border of the symphysis	Line extending from the posterior-superior corner of CV 4 to the posterior-inferior corner of CV 4	Line extending from the base of the epiglottis to the posterior-superior corner of CV 4	Line extending from the posterior-inferior corner of CV 4 to the inferior border of the symphysis
Soft-palate area	Confined by the soft palate that starts and ends at PNS through the uvula tip			
Maxillary sinus	The superior, inferior, medial, and lateral aspects of the maxillary sinus as seen on a section including the maxillary first molar bifurcation			

The prevertebral soft-tissue thickness was measured as the distance parallel to the Frankfort horizontal plane from 6 points on the CV 1, CV 2, CV 3, and CV 4 to the posterior wall of the airway. Bony structure and soft tissue transposed on each other in midsagittal plane with the 3D Dolphin imaging system.

- The most anterior point on the anterior arch of CV 1
- The most inferior-anterior point of CV 2
- The most superior-anterior point of CV 3
- The most inferior-anterior point of CV 3
- The most superior-anterior point of CV 4
- The most inferior-anterior point of CV 4

CV, Cervical vertebra.

passages produces a constant stimulus for lateral growth of the maxilla and lowering of the palatal vault.[4] It is assumed that widening of the nasal passages will produce improved breathing. Gungor and Turkkahraman[5] reviewed the literature evaluating the interaction between respiratory function and maxillary growth pattern. They showed maxillary morphologic differences between subjects with airway problems and the control groups; this suggested a potential etiologic role of the airway in these subjects. RME also caused a significant increase in nasal width and a decrease in maxillary sinus width.[3] Numerous studies have evaluated the effects of maxillary expansion on the airway and found increases in nasal width and volume,[6-8] leading to decreased nasal resistance.[7,9] These findings could be used to recommend future treatment of subjects with constricted airways.

Airway changes after RME have been studied with acoustic rhinometry,[8,10-12] 2 dimensionally (cephalometric methods),[13] and 3 dimensionally (cone-beam computed tomography, computed tomography).[3,14,15] Although there are many studies evaluating the skeletal effects of RME,[16,17] so far only Zhao et al[15] have evaluated the 3-dimensional airway volume changes after RME on the upper airway in control and experimental groups. Therefore, the primary purpose of this retrospective study was to evaluate the airway volume, soft-palate area, and soft-tissue thickness changes before and after RME treatment in adolescent subjects by using 3-dimensional images obtained from computed tomography. The secondary purpose of this study was to determine whether RME causes changes in the palatal and mandibular planes, and in anterior facial height.

MATERIAL AND METHODS

Pretreatment and posttreatment spiral computed tomography images (Xvision EX; Toshiba Medical Systems, Otawara-Shi, Japan) from 20 patients treated with RME were analyzed. The scans were made at 120 kV and 20 mA by using the following protocol: 25-cm field of view, 0.4-mm voxel size, and 2 seconds per section. The scans were taken with the patients in supine position and the palatal plane perpendicular to the floor.[18,19] The study was approved prospectively by the ethical committee of the Faculty of Dental Medicine, Al-Azhar University, Cairo, Egypt, and retrospectively by the institutional review board of Indiana University-Purdue

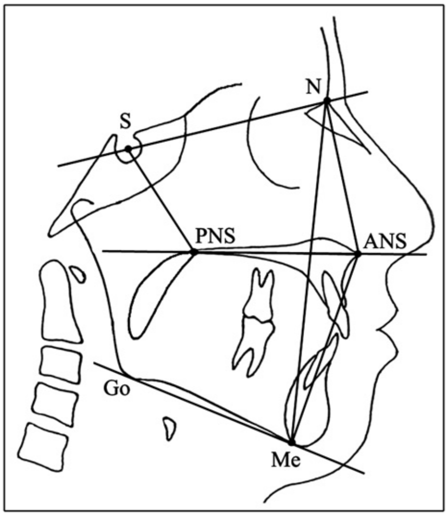

Fig 1. Cephalometric landmarks and planes used in the study: *S*, sella; *N*, nasion; *ANS*, anterior nasal spine; *PNS*, posterior nasal spine; *Me*, menton; *Go*, gonion; *palatal plane*, the horizontal line through ANS and PNS; and *mandibular plane*, the horizontal line through Me and Go.

University at Indianapolis. Inclusion criteria for the study were subjects with bilateral maxillary constriction; age between 8 and 15 years; no previous orthodontic or orthopedic treatment; no systemic diseases, craniofacial anomalies, or temporomandibular joint disorders; no tonsillectomy or adenoidectomy; no carious, gingival, or periodontal lesions; no metallic restorations; and RME planned as a part of comprehensive orthodontic treatment. Our subjects included 8 boys and 12 girls with an average age of 12.3 years ± 1.9 months. The RME appliance used was a Hyrax appliance (Dentaurum, Ispringen, Germany), which included bands on the permanent first molars and first premolars. If the premolars were not present, the bands were cemented to the deciduous first molars. The subjects were instructed to turn the appliance 2 times, twice daily (producing 0.8 mm of expansion daily) until the palatal cusps of the maxillary first molars contacted the buccal cusps of the mandibular first molars. Spiral computed tomography images were taken immediately before the RME and 3 months (91 ± 3.5 days) after the last activation of the appliance.

After training with the scanner (version 11.0; Dolphin Imaging, Chatsworth, Calif), the reliability of the primary investigator (T.S.) was determined by tracing 10 images twice. Since access to the original images was not available at the time, the intrareliability in detecting the anatomic landmarks was done with cone-beam computed tomography scans as the most practical alternative. This could be considered a deficiency in the study

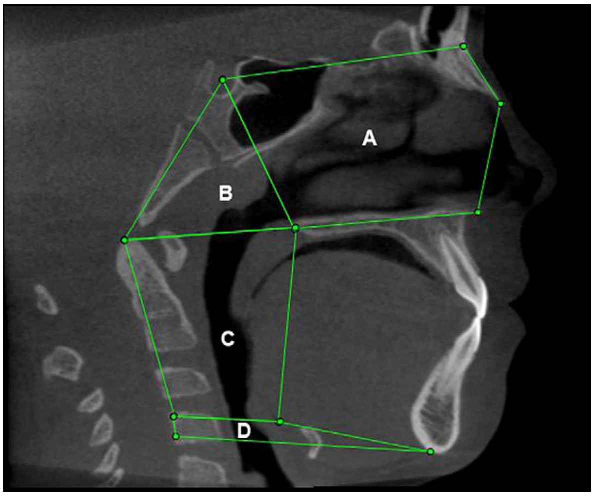

Fig 2. Boundaries of divisions of the airway: *A*, nasal cavity; *B*, nasopharynx; *C*, oropharynx; and *D*, hypopharynx.

concerning the reliability test. Ten cone-beam computed tomographs were chosen randomly from the orthodontic records at the School of Dentistry of Indiana University and coded. Landmarks (Table I) were identified on the tomographs, and the airway volumes were calculated with the Dolphin software. All 10 images were traced again 2 weeks later in random order with the same computer and monitor. An intraclass correlation coefficient equal to or greater than 0.90 was required, or the process would have been repeated 2 weeks later.

Coded computed tomographs were analyzed by using the Dolphin 3D software, on the same computer and monitor (21-in monitor; Dell, Round Rock, Tex; 1680 × 1050 pixels). Although previous 2-dimensional studies have established anatomic landmarks for various airway parameters, 3-dimensional landmarks were required for the analysis of the airway volumes and areas in this study.[20-22] The definitions for the airway parameters, volumetric analysis, and cephalometric measures are presented in Table I and Figures 1-6.

Before landmark identification, the 3-dimensional volumetric images were oriented with the Dolphin imaging software as follows: the midsagittal plane was adjusted on the skeletal midline of the face, the axial plane was adjusted to show the Frankfort horizontal plane (right porion to right orbitale), and the coronal plane was adjusted to pass through the level of the furcation point of the right maxillary first molar (Fig 7).

Statistical analysis

Intrarater reliability was assessed by using Student *t* tests, intraclass correlation coefficients, and Bland-Altman plots. The volumes (maxillary sinuses, nasal cavity,

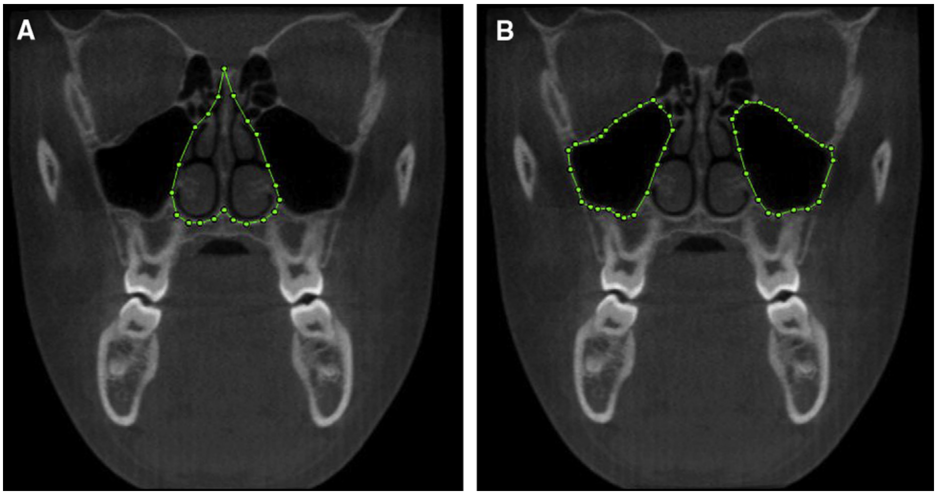

Fig 3. Coronal outline of the boundaries of: **A,** the nasal cavity; and **B,** the maxillary sinuses.

Fig 4. Boundaries of the soft palate.

nasopharynx, oropharynx, and hypopharynx), surface area measurement (soft palate), soft-tissue thickness, and the cephalometric parameters (PP-SN, MP-SN, S-PNS, N-ANS, ANS-Me, and N-Me) before and after RME, and the changes (before to after RME) were summarized with descriptive statistics (means and standard deviations).

Because the before to after RME changes in the measurements were not normally distributed, comparisons between these measurements were made by using Wilcoxon signed rank tests. A P value of ≤ 0.05 was considered statistically significant for both tests. Spearman correlation coefficients were calculated to evaluate the associations among airway volume, soft-palate area, soft-tissue thickness, and cephalometric measurements. All tests were conducted at a 5% significance level with no adjustment for multiple testing. With this sample size, the study had 80% power testing at a 5% significance level to detect a correlation coefficient of 0.55 and a 0.7 SD difference of the before and after RME changes.

RESULTS

The intraexaminer reliability test showed no statistically significant differences between the readings (except for PP-SN and ANS-Me) and excellent intraexaminer reliability (intraclass correlation coefficient, ≥ 0.90) for all measurements (Table II).

Comparisons between the before and after RME measurements showed statistically significant increases only in nasal cavity volume, nasopharynx volume, MP-SN, S-PNS, N-ANS, ANS-Me, and N-Me (Table III, Fig 8).

Significant positive correlations existed between the changes in PP-SN and N-ANS, and ANS-Me and N-Me (Table IV).

DISCUSSION

In this study, we evaluated the cephalometric parameters, airway volume, soft-palate area, and soft-tissue thickness changes before and after RME treatment using 3-dimensional images on the same set of adolescent subjects. Few studies have addressed treatment effects on the airway in the same patient population. RME is a common treatment approach for maxillary constriction, posterior crossbites, and arch length discrepancies, and is recommended to increase airway volume.[23-27] Therefore, it is important to understand the total effect on the upper airway. In addition to airway

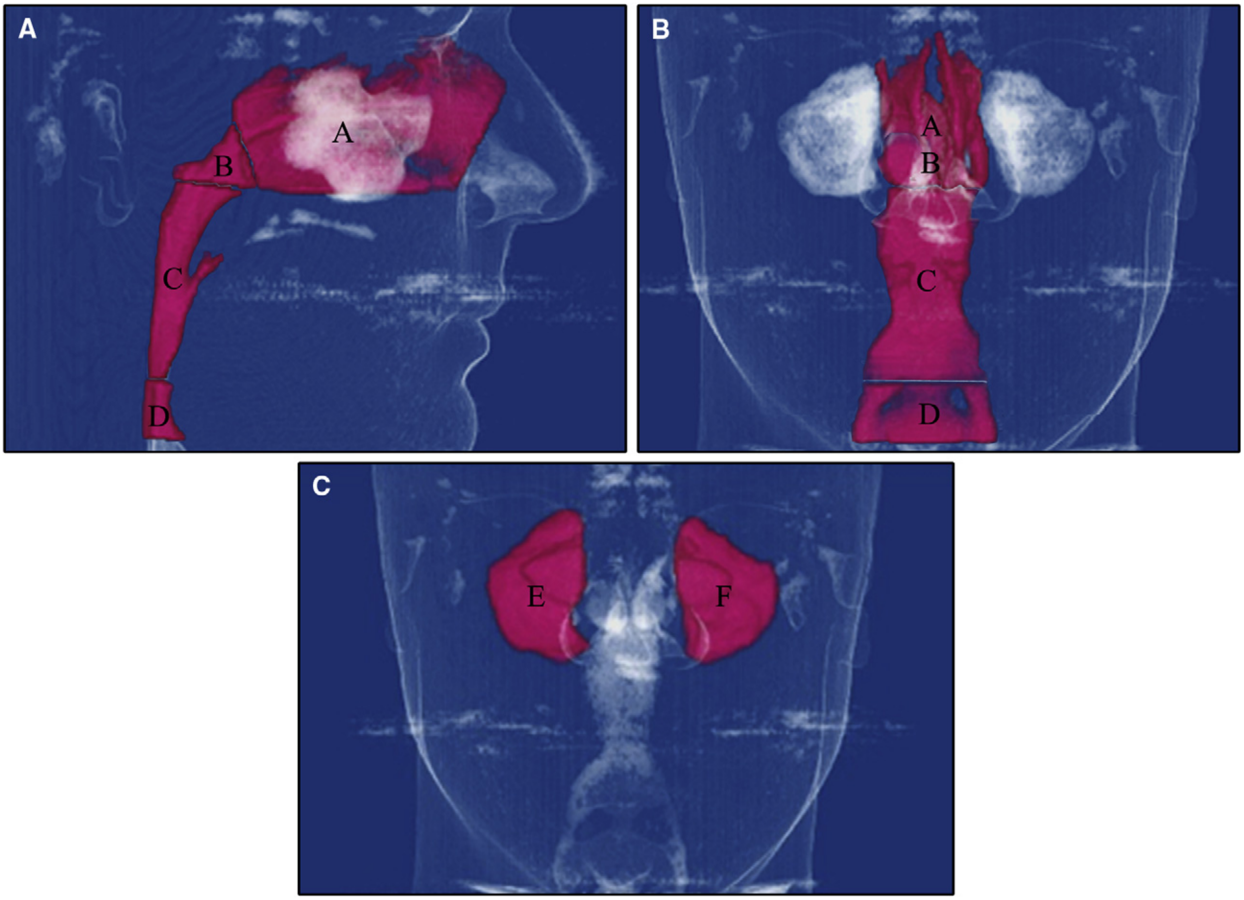

Fig 5. Three-dimensional rendering of the boundaries of the divisions of the airway. **A,** sagittal view of *A*, nasal cavity; *B*, nasopharynx; *C*, oropharynx; *D*, hypopharynx. **B,** Frontal view of *A* and *B*, nasal cavity overlaid on nasopharynx; *C*, oropharynx; and *D*, hypopharynx. **C,** Frontal view of *E*, maxillary right sinus; *F*, maxillary left sinus.

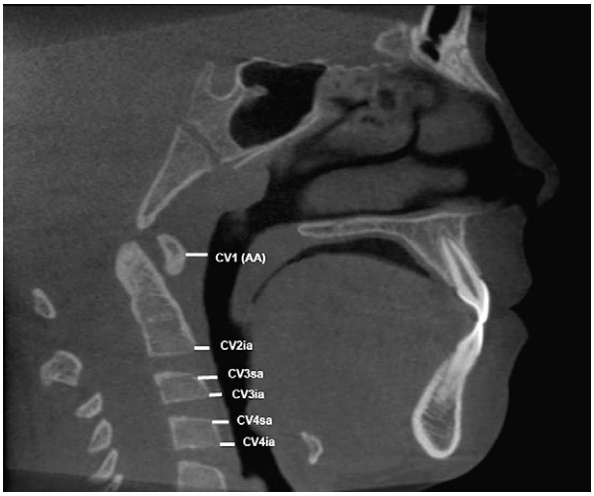

Fig 6. Prevertebral soft-tissue thicknesses measured as horizontal lines drawn from the edges of the vertebrae to the posterior wall of the pharynx (AA-CV4ia).

changes, the following craniofacial structural changes have also been shown: lowering of the palatine vault, lateralization of the inferior nasal turbinates, and lengthening of the nasal septum.[8] Because of these changes, some investigators have stated that RME reduces nasal resistance and increases nasal volume.[7,9,22]

Zhao et al[15] evaluated changes in the volume of the oropharynx in growing patients with maxillary constriction treated by RME. They reported that the oropharyngeal airway volumes in those patients were significantly smaller than in subjects without constriction, and that no evidence supports the hypothesis that RME enlarges the volume of the oropharyngeal airway. In our study, a more complex evaluation of the airway after RME was performed by dividing it into nasopharynx, oropharynx, hypopharnx, and soft-tissue measurements. Before and after RME measurements demonstrated statistically significant increases in nasal cavity and nasopharynx volumes. The volumetric increases observed in this

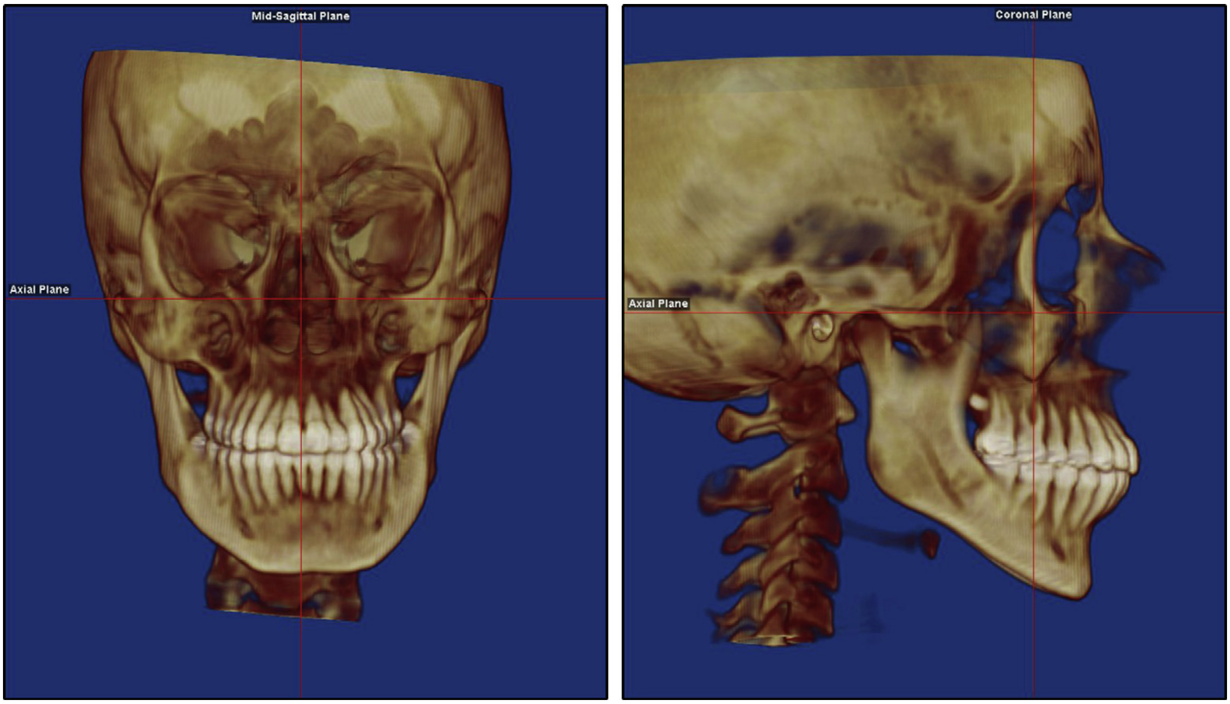

Fig 7. Image orientations: frontal and sagittal views. The midsagittal plane was adjusted on the skeletal midline of the face, the axial plane was adjusted to show the Frankfort horizontal plane (right porion-right orbitale), and the coronal plane was adjusted to pass through the level of the furcation point of the maxillary right first molar.

Table II. Means, standard errors, and intraclass correlations of the airway parameters

	First reading, mean (SE)	*Second reading, mean (SE)*	*Difference, mean (SE)*	P *value*	*Intraclass correlation*
Nasal cavity volume (mm^3)	20048 (1715)	20101 (1715)	53 (97)	0.59	1.00
Nasopharynx volume (mm^3)	5117 (889)	5135 (889)	18 (50)	0.73	1.00
Oropharynx volume (mm^3)	12643 (1710)	12876 (1710)	233 (183)	0.23	0.99
Hypopharynx volume (mm^3)	2780 (473)	2478 (473)	302 (182)	0.13	0.91
Maxillary right sinus volume (mm^3)	14101 (1399)	14130 (1399)	28 (116)	0.81	1.00
Maxillary left sinus volume (mm^3)	13972 (1549)	13938 (1549)	34 (128)	0.80	1.00
Soft palate area (mm^2)	212 (25)	217 (25)	5 (4)	0.32	0.99
Soft-tissue thickness CV 1 (mm)	18.1 (1.1)	18.0 (1.1)	0.1 (0.1)	0.32	1.00
Soft-tissue thickness CV 2 (mm)	3.5 (0.2)	3.4 (0.2)	0.1 (0.1)	0.46	0.96
Soft-tissue thickness CV 3 sa (mm)	4.7 (0.4)	4.7 (0.4)	0.1 (0.1)	0.40	0.99
Soft-tissue thickness CV 3 ia (mm)	3.6 (0.2)	3.6 (0.2)	0.0 (0.1)	0.71	0.95
Soft-tissue thickness CV 4 sa (mm)	4.5 (0.2)	4.5 (0.2)	0.0 (0.1)	1.00	0.97
Soft-tissue thickness CV 4 ia (mm)	4.2 (0.2)	4.2 (0.2)	0.0 (0.1)	0.43	0.97
PP-SN (mm)	7.2 (0.8)	7.7 (0.8)	−0.4 (0.1)	0.01*	0.97
MP-SN (mm)	33.7 (1.9)	33.5 (1.9)	0.1 (0.3)	0.70	0.99
S-PNS (mm)	40.1 (1.2)	39.9 (1.2)	0.2 (0.2)	0.56	0.98
N-ANS (mm)	49.3 (0.9)	48.6 (0.9)	0.7 (0.5)	0.18	0.90
ANS-Me (mm)	65.7 (1.7)	65.0 (1.7)	0.7 (0.3)	0.04*	0.98
N-Me (mm)	113.8 (2.5)	113.3 (2.5)	0.5 (0.6)	0.38	0.97

CV, Cervical vertebra; *sa*, superior-anterior; *ia*, inferior-anterior.
*Significant at $P \leq 0.05$.

Table III. Airway parameters before and after RME and changes

	Before RME *Mean (SD), median*	*After RME* *Mean (SD), median*	*Change* *Mean (SD), median*	*Change (%)*	P *value*
Nasal cavity volume (mm^3)	23950 (6431), 24508	27591 (7775), 25768	3641 (5545), 1868	15.2	0.00*
Nasopharynx volume (mm^3)	3221 (1660), 2878	3744 (1718), 3234	522 (548), 305	16.2	0.00*
Oropharynx volume (mm^3)	10688 (6019), 9001	10504 (5598), 10261	−184 (4335), 581	1.7	0.11
Hypopharynx volume (mm^3)	3319 (1216), 3137	3489 (950), 3598	170 (1021), 96	5.1	0.22
Maxillary right sinus volume (mm^3)	12605 (6077), 12759	12931 (6477), 12175	326 (1898), 230	2.6	0.50
Maxillary left sinus volume (mm^3)	12256 (5925), 12511	12708 (6139), 12884	452 (1825), 208	3.7	0.17
Soft palate (mm^2)	212 (50), 200	208 (37), 201	−4 (45), −10	−1.9	0.52
Soft-tissue thickness CV 1 (mm)	19.4 (4.6), 18.8	18.9 (4.4), 18.5	−0.5 (1.6), −0.4	−2.6	0.27
Soft-tissue thickness CV 2 (mm)	3.4 (0.8), 3.2	3.8 (0.8), 3.5	0.4 (0.9), 0.2	11.8	0.11
Soft-tissue thickness CV 3 sa (mm)	4.5 (1.1), 4.5	4.6 (1.0), 4.5	0.1 (0.9), 0.0	2.2	0.82
Soft-tissue thickness CV 3 ia (mm)	3.8 (1.0), 3.8	4.0 (0.8), 4.0	0.3 (0.7), 0.3	7.9	0.15
Soft-tissue thickness CV 4 sa (mm)	6.1 (1.8), 5.6	6.4 (2.2), 5.7	0.4 (1.2), 0.7	6.6	0.16
Soft-tissue thickness CV 4 ia (mm)	7.2 (2.7), 8.0	7.6 (2.7), 8.1	0.5 (2.2), 0.7	6.9	0.11
PP-SN (mm)	9.4 (4.3), 9.4	9.6 (4.3), 9.2	0.2 (2.3), 0.2	2.1	0.56
MP-SN (mm)	42.7 (7.6), 44.7	43.9 (7.4), 46.0	1.2 (1.1), 1.1	2.8	0.00*
S-PNS (mm)	42.2 (4.2), 41.3	42.9 (4.1), 42.7	0.7 (1.6), 0.5	1.7	0.05*
N-ANS (mm)	53.7 (4.2), 54.5	54.7 (4.4), 55.6	1.0 (2.2), 0.6	1.9	0.03*
ANS-Me (mm)	76.0 (7.3), 76.6	78.7 (8.4), 79.5	2.7 (3.0), 2.2	3.6	0.00*
N-Me (mm)	128.8 (9.3), 130.8	132.2 (10.7), 135.2	3.4 (3.7), 2.4	2.6	0.00*

CV, Cervical vertebra; *sa*, superior-anterior; *ia*, inferior-anterior.
*Significant at $P \leq 0.05$ (signed rank test).

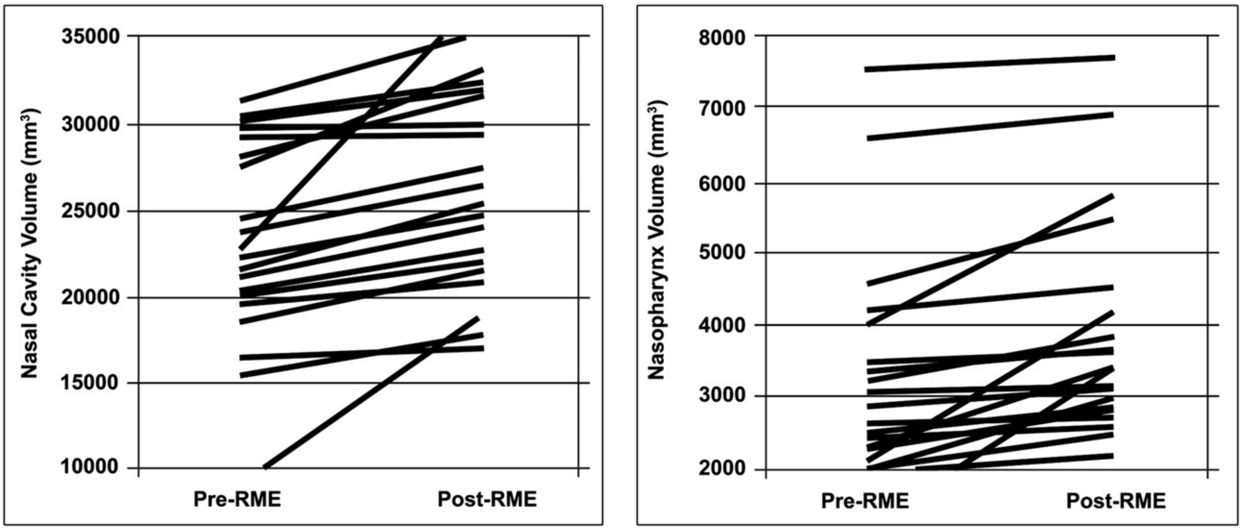

Fig 8. Ladder plots showing the significant increases in nasal cavity and nasopharynx volumes.

3-dimensional study further support airway changes seen in earlier 2-dimensional studies after RME.[7,13,28] Doruk et al[10] used acoustic rhinometry to evaluate nasal airway resistance after RME and found decreased resistance.[10,26] Furthermore, Adkins et al[25] found buccal tipping of the molars and lateral movement of the alveolar process with expansion. Because of this movement, we expected to see distortion of the lower border of the sinuses resulting in a significant increase in maxillary sinus volume after expansion; however, these structural and volumetric changes were not observed. Our findings confirmed those of Zhao et al,[15] who used cone-beam computed tomography to assess changes in the oropharynx volume after RME in growing subjects, to show that the retropalatal airway volume had a statistically significant difference after RME, but the oropharyngeal

Table IV. Significant correlations among measurements

	Before RME		After RME		Change	
	Correlation	P *value*	*Correlation*	P *value*	*Correlation*	P *value*
PP-SN and N-ANS	0.53	0.016*	0.66	0.001*	0.73	0.00*
ANS-Me and N-Me	0.88	0.000*	0.90	0.000*	0.85	0.00*

*Correlation is significant at 0.05 level (Spearman correlation).

volume did not enlarge. Our subjects showed a decrease in oropharynx volume, although the decrease was not significant. The decrease could be explained by the lowering of the palatal plane, just 1 landmark defining the oropharynx.

Our results also showed significant increases in MP-SN, S-PNS, N-ANS, ANS-Me, and N-Me. Jafari et al,[1] using finite element analysis to evaluate the stress distribution and displacement of craniofacial structures after transverse forces were applied, found that the nasomaxillary complex rotated so that lateral structures moved upward and midline structures (including ANS and A-point) moved downward.[8] Kilic and Oktay[29] studied the 2-dimensional vertical changes in the facial skeleton after semirapid maxillary expansion. They found a small downward and backward rotation of the mandible and an increase in facial height. Our findings showed downward movement of ANS, demonstrated by increased upper anterior facial height (distance between ANS and N), thereby contributing to an increased mandibular plane angle (MP-SN), and increases in total and lower anterior facial height (ANS-Me and N-Me). The distance between S and PNS significantly increased, but not as much as between N and ANS. Because of the downward movement of the anterior palate, the increases in N-ANS, ANS-Me, and N-Me were expected. Our findings are supported by a cephalometric study showing that RME caused downward and backward rotation in the palatal plane, thereby altering N-ANS and SN-PP.[13] Molar tipping contributed to the increase in the mandibular plane. The facial heights (N-ANS, ANS-Me, and N-Me) increased as an effect of the vertical displacement of the palate and the increase in the mandibular plane angle.[13] Movement of ANS led to increases in ANS-Me and N-Me. From these findings, positive correlations were expected between PP-SN and N-ANS and between ANS-Me and N-Me.

In this study, the prevertebral soft-tissue thicknesses were measured and compared before and after RME to examine the effect of airway volume changes on soft-tissue thicknesses. The results showed nonsignificant differences in soft-tissue thicknesses; this is consistent with the nonsignificant difference in the oropharynx volume.

Matsumoto et al,[8] usng acoustic rhinometry, computed rhinomanometry, and cephalometrics, demonstrated a significant increase in nasal osseous width after RME, with less significant increases in nasal area and nasal resistance. They concluded that the effects of RME are more evident at the bony level than at the mucosal level; this might be due to compensatory hypertrophy of the nasal mucosa after expansion. Although we limited soft-tissue variations by including only subjects who had not had an adenoidectomy or a tonsillectomy, there could be localized hypertrophy and inflammation after expansion.[8] We established hard-tissue landmarks to define our airway parameters to allow for reproducibility in locating landmarks. The airway volume in these hard-tissue parameters could be altered because of soft-tissue hypertrophy. Nasal resistance can also be due to such factors as nasal polyps, large adenoids, and a deviated septum; however, maxillary expansion increases airway patency by increasing alar width and nasal valve size.[30] Although we evaluated airway volume changes, additional studies are needed to show a relationship between decreased airway resistance and increased airway volume.

CONCLUSIONS

RME causes significant increases in nasal cavity volume, nasopharynx volume, anterior and posterior facial heights, and palatal and mandibular planes.

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