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Analysis of nasal airway symmetry and upper airway changes after rapid maxillary expansion

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Introduction: The objectives of this study were to assess the changes in right vs left nasal cavity volumes and minimum cross-sectional width, nasopharyngeal, and oropharyngeal volumes of the upper airway in response to rapid maxillary expansion (RME). **Methods:** Pretreatment and posttreatment cone-beam computed tomography scans of 28 patients with a mean age of 9.86 ± 2.43 years and 20 age- and sex-matched controls were digitized and linear, angular, and volumetric measurements were obtained. **Results:** Nasopharyngeal volume, right, and left nasal cavity volumes, and minimum cross-sectional widths increased significantly 2 years post RME ($P < 0.05$). These measurements did not show any significant increase in the control group ($P > 0.05$), whereas the oropharyngeal volume increase for both groups was comparable ($P = 0.92$). In the experimental group, the right and left nasal cavity volumes were not significantly different at baseline or posttreatment. However, the change that occurred was significantly larger for the left nasal cavity. This change for the control group was more significant for the right nasal cavity. Maxillary right and left molar inclinations were positively correlated to the nasal cavity volume, showing that the more buccally inclined the maxillary molars were, the smaller the nasal cavity volume. **Conclusions:** Nasopharyngeal and right and left nasal cavity volumes and minimum cross-sectional widths increase significantly after RME in young children. Expansion decreases the degree of difference in volume between the right and left nasal cavities. The buccal inclination of maxillary molars is correlated with nasal cavity volume. (Am J Orthod Dentofacial Orthop 2021;160:695-704)

Rapid maxillary expansion (RME) is the treatment of choice for constricted maxillary arches in growing patients. It is routinely used to correct unilateral and bilateral crossbites, alleviate tooth size-arch length discrepancies and dental impactions.[1-3] To resolve the maxillary transverse deficiency, a tooth-borne expander transmits force to the maxilla and its neighboring bones, causing the separation of several cranial and circummaxillary sutures.[4] Resistance to the separation of maxillary halves lies mainly in the zygomatic and sphenoid bones leading to a pyramidal pattern of opening with outward tilting of maxillary halves and causing greater opening at the dentoalveolar level inferiorly and anteriorly.[1,2,5] Considering this pattern of expansion and the anatomic proximity of the maxilla and nasal cavity, it can be anticipated that maxillary expansion moves the external walls of the nasal cavity laterally, increasing nasal width, volume, and the cross-sectional area mostly at the levels of inferior turbinates.[2,5-11] Several studies have shown that the increase in these nasal parameters through maxillary expansion reduces nasal airway resistance and improves nasal respiration.[12-15]

A number of anatomic and nonanatomic features have been recognized as contributing factors to the narrowing of the airway that may predispose the individual to sleep-related breathing disorders (SRBDs).[16,17] Obesity and craniofacial abnormalities, including retrognathic mandible, small and constricted maxilla, and low position of the hyoid bone, have been indicated as contributing anatomic features.[18-20] Maxillary deficiency has been shown to affect nasal resistance, tongue posture, and upper airway dimensions.[14,17,18,21] Although a causal

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relationship between dentofacial form and nasal breathing cannot be confirmed, nasopharyngeal obstruction has been associated with deficient facial growth contributing to increased facial height, narrow maxillary arch, steep mandibular plane angle, and increased craniocervical angulation.[17,22] Therefore, addressing these craniofacial abnormalities at a younger age while maxillary suture opening is more feasible can lead to a more pronounced and stable gain in nasal width and minimum cross-sectional area, a major contributor to nasal airway resistance, and may help improve breathing and possibly prevent the development of SRBDs in the future.[11,23,24] As recommended by the American Association of Orthodontists' recent white paper on obstructive sleep apnea and orthodontics, the primary objective of RME is to normalize maxillary transverse deficiency and improve occlusion, whereas a secondary positive impact of increasing upper airway volume and reducing nasal resistance may make it a plausible treatment modality in children with SRBDs.[14,25-31]

Bilateral structures have been shown to grow to different degrees. Such laterality is seen throughout the body, and craniofacial structures are no exception when it can be presented as normal asymmetry, dental and skeletal midline deviations, and other right and left size differences. Genetic and environmental etiologic factors have been suggested for this phenomenon.[32-34] To the best of our knowledge, there was only one study[35] that evaluated the effect of RME on the right vs left nasal cavities using conventional tomography. Several other studies have reported on the short-term effects of RME on nasal cavity[24,36-40] and the nasopharyngeal and oropharyngeal[37,38,40-44] airway volumes, and the majority of these studies evaluated the adolescent population.

The objectives of this study were to (1) evaluate the effect of RME on the right and left nasal cavities in terms of volumetric and minimum cross-sectional width changes, (2) evaluate the impact of RME on nasal cavity and nasopharyngeal and oropharyngeal airway volumes in young children over the long term in comparison with a control group, and (3) evaluate the relationship between maxillary molar divergence and nasal cavity volume.

MATERIAL AND METHODS

This retrospective study was approved by the Boston University Institutional Review Board (no. H-34714). A deidentified cone-beam computed tomography (CBCT) repository and coded medical and dental records (no. H-32515) were screened on the basis of the following inclusion criteria: (1) diagnostic preorthodontic and postorthodontic treatment CBCT images (2) nonsyndromic patients, (3) no history of adenotonsillectomy, (4) nonsurgical expansion, and (5) successful skeletal maxillary expansion as verified by measuring the distance between right and left greater palatine foramina on CBCT images. All subjects completed treatment involving RME using a banded hyrax expander cemented to the maxillary first molars. The activation protocol followed was 1 turn per day (0.25 mm/turn) until overcorrection was achieved. The expander was maintained for 3 months postexpansion, and subsequent orthodontic treatment was carried out with edgewise appliances. The same repository was screened for selection of the control group, which consisted of CBCT scans of age- and sex-matched patients who did not present with maxillary deficiency and were not deemed to benefit from orthopedic expansion, taken before the start of orthodontic treatment and after appliance removal. The demographic information for the experimental and control groups can be found in Table I.

Table I. Demographic information

Demographics	*Experimental group*	*Control group*	P
Gender, %			0.77*
Male	39.29	45.00	
Female	60.71	55.00	
Age, mean (SD)	9.86 (2.43)	10.41 (1.60)	0.1**

SD, standard deviation.
*Chi-square test; **Student *t* test.

The sample included 28 subjects (11 males, 17 females) with a mean age of 9.86 ± 2.43 years at the time of the initial scan. The control group consisted of 20 subjects (9 male, 11 female) with a mean age of 10.41 ± 1.60 years at the time of the initial scan. All CBCT scans were taken using the same iCAT machine (Imaging Sciences International, Hatfield, Pa) operated at 120 kVp, 5 mA, and 0.5 mm nominal focal spot size, rendering a 17.0 cm × 23 cm field of view with a 0.3 mm voxel size image. Patients were seated in a chair and were instructed to hold their heads in natural head position and avoid swallowing. The acquired scans were then exported as Digital Imaging and Communications in Medicine files and were processed and segmented by 2 of the authors (C.D. and C.S.) using Mimics software (version 20; Materialise, Leuven, Belgium). First, predetermined and/or custom threshold limits were selected for soft and hard tissue masks to be created. Empty spaces were delineated as the airway mask, and the connection with the outer air was eliminated.

A 3-dimensional (3D) rendering of the airway was then created by the software. Soft and hard tissue landmarks (Table II) were digitized on their corresponding

Table II. Description of points used for airway segmentation

Point	*Description*
Anterior nasal spine	Most anterior and midline point of anterior nasal spine
Posterior nasal spine	Most posterior and midline portion of palate
Ala right	Most outside portion of soft tissue ala
Ala left	Most outside portion of soft tissue ala
C3	Most anterior inferior and medial portion of C3 vertebrae
Greater palatine foramen right	Most anterior and inferior portion of right greater palatine foramen
Greater palatine foramen left	Most anterior and inferior portion of left greater palatine foramen
Infraorbital foramen right	Inferior and mid infraorbital foramen
Infraorbital foramen left	Inferior and mid infraorbital foramen
Midnasal bone	Midway between nasion and nasal tip using "measure over surface" function in Mimics
Nasion	Intersection of nasal and frontal suture at its midpoint
Aperture piriformis right	Widest portion of aperture piriformis right
Aperture piriformis left	Widest portion of aperture piriformis left
Pronasale	Middle most tip of soft tissue of nose
Nasal tip	Tip of nasal bone
Zygomaticotemporal suture superior right	Most superior portion of suture
Zygomaticotemporal suture superior left	Most superior portion of suture
Zygomaticotemporal suture inferior right	Most inferior portion of suture

masks, and their appropriate locations were verified on axial, sagittal, and coronal slices. These landmarks were used to construct reference planes and dissector planes as described in Table III. The dissector planes were used to segment the upper airway into the nasal cavity, nasopharynx, and oropharynx. Right and left nasal cavity separation was evident through anatomic hard tissue between the 2 compartments, as shown in the Figure. The volume of each segment was then calculated. By screening every slice on the coronal view, the narrowest portion of the left and right nasal airway was determined. To verify this narrowest portion, 5 ventral and 5 dorsal slices were remeasured and the slice with the narrowest width was selected. The number of slices from point pronasale to this narrowest width was recorded on the pretreatment scans to be consistent in measuring the same position on the posttreatment scans. Maxillary molar inclinations on initial scans were measured after previously established methodology by Miner et al,[45] measuring the angle between the long axis lines of the maxillary right and maxillary left first molars and the functional occlusal plane.

Table III. Description of planes used for airway segmentation

Planes	*Description*
Reference planes	
Frankfort Derivative plane (FD)	A plane passing through infraorbital foramen left and right and most inferior point on the right zygomaticotemporal suture
Vertical nasal plane	A plane passing through nasion and the right and left piriform apertures
Dissector planes	
Superior border	A plane through midnasal point and most superior point on right and left zygomaticotemporal sutures
PNS plane (inferior border)	A plane through PNS point parallel to FD
PNS vertical plane	A plane passing through PNS point parallel to vertical nasal plane
Pronasale plane	A plane passing through pronasale and right and left ala
C3	A plane passing through C3 point parallel to FD

PNS, posterior nasal spine.

To assess intrarater and interrater reliability, a random sample (10% of the overall sample) was remeasured by the same 2 operators (C.D. and C.S.) approximately 4 weeks after initial measurements were made. For all measurements, the intraclass correlation coefficient values were >0.80 (ie, indicating good reliability), and using paired *t* test, no measurement was found to be significantly different at the $P < 0.05$ level.

Paired *t* tests were used to compare the initial and postexpansion volumetric and minimum cross-sectional width changes after RME procedure and the initial left and right molar angulation differences before RME treatment. Student *t* tests were also used to analyze changes in volume and minimum cross-sectional width between the experimental and control groups. Pearson correlation test was utilized to test the relationship between initial molar angulation and initial nasal cavity volume. All statistical analysis was completed using SAS software (version 9.4; SAS, Cary, NC). Statistical significance was set at the 0.05 level.

RESULTS

All subjects and controls were growing patients who had received orthodontic treatment with (experimental group) or without (control group) RME. The average time interval between initial and final scans for

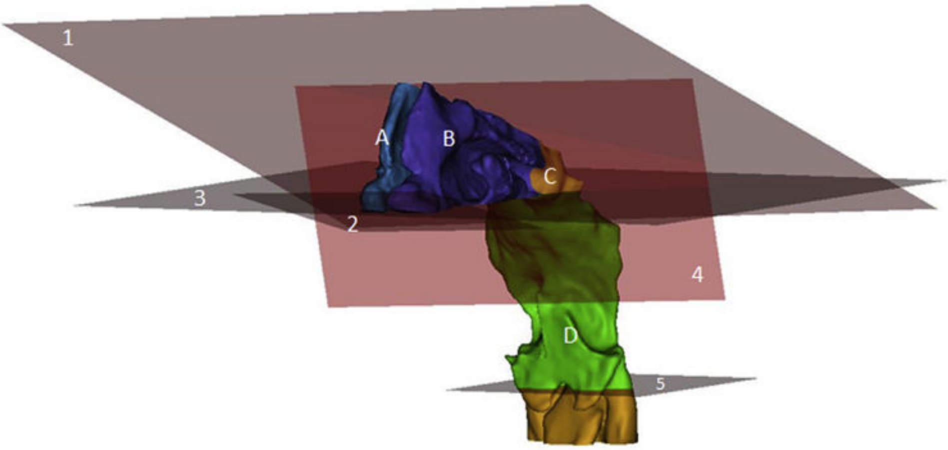

Fig. Upper airway segments: **A,** right nasal cavity; **B,** left nasal cavity; **C,** nasopharygneal volume; **D,** oropharyngeal volume. Dissector planes: **1,** superior plane, that is the plane passing through midnasal point and the right and left superior zygomaticotemporal suture; **2,** pronasale plane, that is the plane passing through pronasale and right and left ala nasi; **3,** posterior nasal spine plane (inferior border), that is the plane passing through the posterior nasal spine and parallel to the Frankfort derivative plane; **4,** posterior nasal spine vertical, that is the plane passing through posterior nasal spine and parallel to the vertical nasal plane; **5,** C3 plane, that is the plane passing through the most anterior inferior point on C3 and parallel to the Frankfort derivative plane.

the control and experimental groups were 20.6 ± 2.14 months and 24.4 ± 10.79 months, respectively. The difference is 3.8 ± 2.1 months which was not significant ($P = 0.13$). In addition, there was no statistically significant difference between the 2 groups with respect to age and sex distribution, as shown in Table I.

The successful skeletal expansion was verified by the increase in linear distances between most anterior inferior points on the right and left greater palatine foramina of 2.41 ± 1.03 mm ($P < 0.01$) as measured on the CBCT scans. Volumetric analysis of right and left nasal cavity, total nasal cavity, nasopharyngeal and oropharyngeal segments of the upper airway all showed a significant increase 2 years posttreatment, with the greatest percentage change seen in the nasopharynx with a 43.92% increase and the least seen in the right nasal cavity with a 26.53% increase (Table IV). In the control group, the only significant increase in volume occurred in the oropharyngeal airway ($P = 0.03$), whereas the increase in other compartments was not statistically significant (Table V). Comparison of the volumetric changes in all compartments between the experimental and control groups showed the difference between the 2 groups to be significant in all segments except the oropharyngeal compartment ($P = 0.92$) (Table VI).

For the experimental group, there was no significant difference between the right and left nasal cavity volumes at baseline ($P = 0.35$). Posttreatment right and left nasal volumes were also not significantly different ($P = 0.81$). However, the change occurring in response to treatment was significantly different comparing the left to the right side, showing a more significant increase on the left side, which had a lower baseline volume (Table VII). In the control group, the baseline volumes of the right and left nasal cavities were also not significantly different ($P = 0.53$), and the same was true for their posttreatment volumes ($P = 0.14$). The change that occurred in the right and left cavities, between the initial and final scans, was significantly greater for the right side (Table VIII).

The minimum cross-sectional width was consistently located at the level of the middle turbinate for all but one subject, for whom it was at the level of the inferior turbinate. Measurements showed highly symmetrical and statistically significant increases of 0.13 ± 0.07 mm and 0.11 ± 0.06 mm for the right and left side, respectively, following RME (Table IX). The increase in minimum cross-sectional width was not significant for either the right or left nasal cavities in the control group (Table X), and a comparison between the control and experimental groups showed that the changes occurring in minimum cross-sectional width were significantly larger for both right and left nasal cavities in the experimental group (Table XI).

On the initial scans of the experimental group, maxillary right and left molar angulation to functional

Table IV. Volumetric analysis before (T1) and after (T2) treatment for the experimental group

Volumetric variable	*T1, mean ± SD (mm^3)*	*T2, mean ± SD (mm^3)*	*T2-T1, mean ± SD (mm^3)*	*95% CI (mm^3)*	P	*Percent increase*
Total nasal cavity	7971.6 ± 1801	10082.90 ± 2551.73	2249.6 ± 2102.5	1361.8-3137.4	<0.0001	30.82
Right nasal cavity	4094.90 ± 1079.66	5063 ± 1323.3	968.8 ± 1082.7	549-1388.6	<0.0001	26.53
Left nasal cavity	3813.10 ± 1138.28	4970.3 ± 1564.43	1197.3 ± 1587	569.5-1825.1	0.0006	38.82
Nasopharynx	2815.88 ± 1037.34	3816.44 ± 1053.21	1000.6 ± 917.7	629.9-1371.2	<0.0001	43.92
Oropharynx	7645.22 ± 2311.72	9994.40 ± 3511.89	2349.2 ± 2520.8	1308.6-3389.7	<0.0001	33.76

Note. Significant at *P* <0.05.
T1, initial; *SD*, standard deviation; *T2*, postexpansion; *CI*, confidence interval.

Table V. Volumetric analysis before (T1) and after (T2) treatment for the control group

Volumetric variable	*T1, mean ± SD (mm^3)*	*T2, mean ± SD (mm^3)*	*T2-T1, mean ± SD (mm^3)*	*95% CI (mm^3)*	P	*Percent increase*
Total nasal cavity	7655.0 ± 2037.27	8027.34 ± 1807.87	372.3 ± 1456.1	−309 to 1053.8	0.27	7.38
Right nasal cavity	3954.0 ± 1375.53	4304.0 ± 1421.46	349.9 ± 826.7	−37.0 to 736.8	0.073	11.78
Left nasal cavity	3701.0 ± 1113.24	3723.39 ± 947.17	22.44 ± 1313.4	−592.2 to 637.1	0.94	6.42
Nasopharynx	2716.90 ± 11,371.24	2908.30 ± 1256.0	191.4 ± 855.9	−209.2 to 592.0	0.33	23.97
Oropharynx	8307.0 ± 3383.73	10551.0 ± 3680.72	2244.0 ± 4345.1	210.0 to 4277.6	0.03	41.56

Note. Significant at *P* <0.05.
T1, initial; *SD*, standard deviation; *T2*, postexpansion; *CI*, confidence interval.

Table VI. Comparison of volumetric changes between the experimental and control groups

	Mean difference ± standard deviation (mm^3)			
Volumetric variable	*Experiment group*	*Control group*	*Experiment − control group*	P
Total nasal cavity	2249.6 ± 2102.5	372.3 ± 1456.1	1780.4 ± 1807.0	0.002
Right nasal cavity	968.8 ± 1082.7	349.9 ± 826.7	618.9 ± 985.1	0.04
Left nasal cavity	1197.3 ± 1587	22.44 ± 1313.4	1174.9 ± 1477.7	0.01
Nasopharynx	1000.6 ± 917.7	191.4 ± 855.9	809.2 ± 891.5	0.004
Oropharynx	2349.2 ± 2520.8	2244.0 ± 4345.1	105.1 ± 3448.0	0.92

Table VII. Initial, posttreatment, and difference comparison for right and left nasal cavity volumetric analysis for the experimental group

Volumetric variable	*Mean difference left to right side (mm^3)*	*95% CI (mm^3)*	P
Initial nasal cavity	281.8 ± 296.49	−312.62 to 876.22	0.35
Postexpansion nasal cavity	92.7 ± 387.23	−683.65 to 869.05	0.81
Postexpansion − initial nasal cavity	189.1 ± 92.2	4.31 to 373.89	0.045

Note. Significant at *P* <0.05.
CI, confidence interval.

Table VIII. Initial, follow-up, and difference comparison for right and left nasal cavity volumetric analysis for the control group

Volumetric variable	*Mean difference left to right side (mm^3)*	*95% CI (mm^3)*	P
Initial nasal cavity	253 ± 395.69	−548.03 to 1054.03	0.53
Follow-up nasal cavity	580 ± 381.95	−192.60 to 1353.82	0.14
Follow-up − initial nasal cavity	−327 ± 122.97	−575.95 to−78.05	0.01

Note. Significant at *P* <0.05.
CI, confidence interval.

Table IX. Minimum cross-sectional width measurements of the right and left nasal cavities before (T1) and after (T2) treatment for the experimental group

Cross-sectional variable	*T1, mean ± SD (mm)*	*T2, mean ± SD (mm)*	*T2-T1, mean ± SD (mm)*	*95% CI (mm)*	P	*Percent increase*
Cross-sectional width right	0.34 ± 0.09	0.47 ± 0.12	0.13 ± 0.07	0.10-0.16	<0.0001	41.14
Cross-sectional width left	0.33 ± 0.08	0.45 ± 0.11	0.11 ± 0.06	0.09-0.14	<0.0001	38.53

Note. Significant at $P < 0.05$.
T1, initial; *SD*, standard deviation; *T2*, postexpansion; *CI*, confidence interval.

Table X. Minimum cross-sectional width measurements of the right and left nasal cavities before (T1) and after (T2) treatment for the control group

Cross-sectional variable	*T1, mean ± SD (mm)*	*T2, mean ± SD (mm)*	*T2-T1, mean ± SD (mm)*	*95% CI (mm)*	P	*Percent increase*
Cross-sectional width right	0.37 ± 0.11	0.41 ± 0.13	0.04 ± 0.15	0.03 to 0.10	0.27	17.42
Cross-sectional width left	0.42 ± 0.15	0.38 ± 0.14	−0.04 ± 0.22	−0.15 to 0.06	0.42	6.77

Note. Significant P value at $\alpha < 0.05$.
T1, initial; *SD*, standard deviation; *T2*, postexpansion; *CI*, confidence interval.

Table XI. Comparison of cross-sectional width measurements of the right and left nasal cavities between the experimental and control groups

	Mean difference ± SD (mm^3)				
Cross-sectional variable	*Experimental group*	*Control group*	*Experimental − control group*	*95% CI*	P
Cross-sectional width right nasal cavity	0.13 ± 0.07	0.03 ± 0.14	0.10 ± 0.11	0.03-0.16	0.004
Cross-sectional width left nasal cavity	0.12 ± 0.07	−0.04 ± 0.14	0.16 ± 0.15	0.098-0.22	0.0001

Note. Significant at $P < 0.05$.
CI, confidence interval.

Table XII. Maxillary right and left molar angulations and comparison between expeimental and control groups

Variable	*Mean*	*SD*	*Minimum*	*Maximum*	P
Maxillary right first molar angle (experimental)	79.7°	3.98°	73.4°	86.6°	–
Maxillary left first molar angle (experimental)	77.4°	4.40°	68.4°	84.3°	–
Maxillary right to left first molar angle comparison (experimental)	2.28°	4.54°	0.52°	4.04°	0.01
Maxillary right first molar angle (control)	74.63°	6.32°	64.78°	88.32°	–
Maxillary left first molar angle (control)	71.14°	6.79°	53.78°	80.71°	–
Maxillary right to left molar angle comparison (control)	3.49°	6.29°	0.55°	6.44°	0.02
Experimental − control	−1.21°	1.65°	−4.57°	2.15°	0.47

Note. Significant at $P < 0.05$.
CI, confidence interval.

occlusal plane averaged 79.7° ± 3.98° and 77.4° ± 4.40°, respectively. There was a statistically significant difference in molar angulation between the right and left ($P = 0.01$). In the control group the average maxillary right and left molar inclinations to functional occlusal planes were significantly different (74.63° ± 6.32° and 71.14° ± 6.79°, $P = 0.02$). There was no significant difference between the experimental

Table XIII. Pearson correlation coefficient table for the relationship between initial maxillary molar angulation and initial volume (pooled sample)

Molar angulation to functional occlusal plane	*Right NC* *r-value (P-value)*	*Left NC* *r-value (P-value)*	*Total NC* *r-value (P-value)*
Maxillary right molar angle	0.28 (0.05)	0.38 (0.007)	0.40 (0.005)
Maxillary left molar angle	0.26 (0.07)	0.35 (0.02)	0.37 (0.009)

NC, nasal cavity.
Note. Significant P value at $\alpha < 0.05$.

and control groups in regard to the right to left molar angulations ($P = 0.47$), as shown in Table XII. The initial scans of experimental and control groups were pooled together to evaluate the relationship between molar inclination and nasal cavity volume in the untreated population. Maxillary right and left molar inclinations were positively correlated to the nasal cavity volume, showing that the more buccally tipped the maxillary molars, the smaller the nasal cavity volume (Table XIII).

DISCUSSION

Nasal, nasopharyngeal, and oropharyngeal cavities have been evaluated by different imaging techniques. Traditional 2-dimensional cephalometry is limited to linear measurements of the airway and lacks the details needed to reliably depict the limits of nasal and nasopharyngeal and oropharyngeal cavities. Magnetic resonance imaging, computed tomography (CT), and CBCT allow for 3D reconstruction and visualization of the upper airway at different levels and make volumetric measurements of the different airway compartments possible. CBCT is an accessible option to the dentist and incurs lower cost than magnetic resonance imaging and conventional CT while providing a low radiation option with the accuracy needed in linear and volumetric measurements of the upper airway.[46,47] In addition, a high level of agreement has previously been reported between acoustic rhinometry and CT or CBCT measurements of the airway.[6,24] Three-dimensional software such as that used in this study allow for 3D reconstruction and precise segmentation of the airway and provide reliable and reproducible 3D measurements and morphologic evaluation of skeletal, soft tissue, and airway compartments.[24,48]

This study was a retrospective evaluation of the long-term effects of RME on the different levels of upper airway and its effect on the right vs left nasal cavity in young children. Because of the long-term nature of this study, the effect of growth on airway size could be considered a confounding factor. To address this concern, a sex- and age-matched group of controls, with a similar time lapse between the 2 time points of CBCT scans, were selected (Table I). All compartments of the upper airway showed a significant increase in volume in the experimental group, as seen in Table IV. For the control group, all compartments also showed an increase in volume, but this increase was only significant in the oropharyngeal volume (Table V). Therefore, the significant increase in right and left nasal cavities and nasopharyngeal airway in the experimental group over 20.6 ± 2.14 months cannot be attributed to growth alone. A study[36] on a similar age group but a smaller sample size showed a significant increase in the nasal volume of 1270 ± 650 mm^3, 7 months after RME. The authors' finding is smaller than the change in nasal volume in our sample (2249.6 ± 2102.5 mm^3), which could be attributed to their segmentation of only the lower portion of the nasal cavity. Other studies evaluated this change in older patients. Görgülü et al,[39] and Doruk et al,[6] showed an increase in the nasal volume of 12.14% and 11.16%, respectively, 6 months post RME treatment on 12-14-year-old patients. Other studies on the adolescent age group similarly found a lower percentage of increase 8.1%[49] and 15.2%[40] at 3 months postexpansion. As noted before, this discrepancy in findings is likely to be associated with the difference in age groups, with the younger population showing a more significant increase in nasal airway volume.[43] Our study on a younger population (mean age, 9.86 ± 2.43 years) showed a higher percentage increase in nasal airway volume postexpansion (30.82%). Although some of this long-term increase can be attributed to growth increases, growth alone over a similar period did not result in a significant increase in volume. Comparing the change in volume occurring between the experimental and control groups showed a greater increase for the experimental group (Tables IV and V). To the best of our knowledge, there were no other studies evaluating the long-term effects of RME on nasal volume on 3D images to compare with our results. It is important to note that the current study did not include polysomnography data to correlate with the nasal and nasopharyngeal airway changes. In addition, the correlation between incremental change in maxillary width and volumetric and minimum cross-sectional areas of the nasal and nasopharyngeal and oropharyngeal airway was not possible because the average amount of expansion was not large enough for this type of analysis.

Several CBCT studies[42,50,51] reported changes in the volume of the nasopharyngeal airway in response to RME in the short term but could not be compared with our findings because of significantly different methodology in the designation of the nasopharyngeal borders. Smith et al[40] and Almuzian et al,[38] reported an increase of 16% and 13.4% in nasopharyngeal volume, 3 months and 23 days after RME, respectively. However, their patient population (average age 12 years) was older than our study.

Although the increase in oropharyngeal volume was significant in our experimental group, this effect cannot merely be attributed to the effect of RME as there was no significant difference between the experimental and the control groups when comparing the change occurring in this segment of the upper airway (Table VI). Our findings are in agreement with other studies[43,52,53] that found a significant increase in oropharyngeal volume in response to RME over the long term; however, the increase was not significantly different than the control groups included and this was true for both younger and older patient populations. Other studies[40,41] did not find a significant change 3-4 months after RME in the oropharyngeal (retropalatal and retroglossal) airway volume. These discrepancies in findings in relation to the oropharyngeal area may be due to the difficulty in standardizing tongue posture and head position during image acquisition which can influence the volume of this segment.[42]

The right hemiface has been shown to be the wider side, especially during childhood and later in life, and there seems to be a decrease in the proportion of patients with the wider right side.[34,54-57] In our study, the experimental group showed no significant difference between the right and left nasal cavity volumes before RME and at the time of the final scan. However, the change that occurred in the volume of right and left nasal cavities posttreatment was significantly different between the 2 sides. The left side started with a smaller volume than the right side (3813.10 ± 1138.28 mm^3 vs 4094.90 ± 1079.66 mm^3). The change in volume recorded posttreatment was significantly different between the 2 sides ($P = 0.045$), showing that there was a higher increase in the volume of the left nasal cavity that had a smaller volume at the initial time point (Tables IV and VII). This may be a balancing effect of expansion in which the behavior of the nasal septum leads to a more significant increase on the smaller side. In the control group, the initial and final volumes of the right and left nasal cavities were comparable ($P = 0.53$ and $P = 0.14$, respectively), as shown in Table VIII. The right nasal cavity showed more of an increase than the left nasal cavity, 11.78% ($P = 0.07$) vs 6.42% ($P = 0.94$), but that was not significant (Table V). However, the amount of increase in the volume of the right nasal cavity was significantly greater than the amount of increase in the volume of the left nasal cavity ($P = 0.01$), showing that, unlike the experimental group, the side that started smaller stayed smaller and the larger side showed a greater increase. Only one other study[35] was found that evaluated the short-term effects of RME on nasal cavity symmetry using conventional tomography. In contrast to our findings, they did not find a significant difference between changes in left vs right nasal cavity volumes. By these findings, it may be speculated that after RME, the growth of the right and left nasal cavity assumes a more normal pattern, possibly because of the correction of nasal septum shape. However, confirmation of this effect is beyond the scope of this study.

Areas of relative constriction have a more significant role in airway resistance than volume. Evaluating the minimum cross-sectional width of the right and left nasal cavities determined in the coronal plane showed a significant increase of 0.13 ± 0.07 mm (41.14%) and 0.11 ± 0.06 mm (38.53%) on the right and the left sides, respectively (Table IX). This change in the control group was not significant for either of the nasal cavities (Table X), and a comparison between the control and experimental groups showed a significant difference, alluding to the impact of RME in increasing the minimal cross-sectional width of both right and left nasal cavities when controlled for growth (Table XI). Basciftci et al[58] and Wertz,[9] evaluated changes in the width of the nasal cavity in response to RME on posteroanterior cephalograms and found a significant increase of 3.47 mm and 1.9 mm, respectively. However, these studies only reported on the linear changes in the widest portion of the nasal cavity and not the minimum cross-sectional width. Acoustic rhinometry studies[10,15,23] have previously reported significant increases in the minimum cross-sectional area of the nasal passages in response to RME. However, measurement of the minimum cross-sectional area of the right and left nasal cavity on CBCT scans was not possible in our study because of software limitations.

Evaluation of maxillary molar inclinations before any treatment relative to the functional occlusal plane showed a significant difference between the right and left molars in both experimental and control groups (Table XII). For both groups, maxillary right molars appeared to be more upright when compared with the left side. Maxillary molar inclination was shown to be correlated positively with nasal cavity volume (Table XIII). The smaller the nasal cavity volume, the more buccally inclined the molars were. It can be concluded that dental compensation of the maxillary molars, especially as seen in patients with maxillary constriction, can be correlated with a smaller nasal cavity and should be used as a warning sign to correct with RME.

CONCLUSIONS

1. Maxillary expansion shows a significant increase in nasal volume and minimum cross-sectional width and nasopharyngeal volume 2 years posttreatment when compared with a control group.
2. Maxillary expansion decreases the degree of volume difference between right and left nasal cavities in the long term.
3. Increased dental compensation of the maxillary molars (buccal tipping), especially as seen in patients with maxillary constriction, can be correlated with smaller nasal cavity volume.

AUTHOR CREDIT STATEMENT

Charles DiCosimo contributed to investigation and original draft preparation; Ahmed A. Alsulaiman contributed to formal analysis, review, and editing; Charmi Shah contributed to validation and investigation; Melih Motro contributed to conceptualization, methodology, and review and editing; Leslie A. Will contributed to supervision, review and editing, and resources; Goli K. Parsi contributed to conceptualization, methodology, original draft preparation, and review and editing.

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