

Clinical Paper  
Orthognathic Surgery

# Volumetric changes of the upper airway following maxillary and mandibular advancement using cone beam computed tomography

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**Abstract.** The objective of this project was to retrospectively evaluate changes in volume of different compartments of the upper airway in response to maxillary, mandibular, and bimaxillary advancement surgeries and to predict the extent of volumetric changes associated with these surgical movements. Pre- and post-surgical cone beam computed tomography scans of 36 patients were evaluated for changes in nasal cavity, nasopharyngeal, oropharyngeal, and hypopharyngeal compartments. The amount of movement for each surgery was measured from skeletal landmarks to reference planes and was correlated with volumetric changes. Maxillary advancement of  $4.0 \pm 2.2$  mm increased the oropharyngeal volume significantly (41.40%), and mandibular advancement of  $3.8 \pm 1.6$  mm also significantly increased the oropharyngeal volume (21.17%). Bimaxillary advancement of  $5.1 \pm 1.3$  mm for the maxilla and  $6.4 \pm 3.1$  mm for the mandible significantly increased nasopharyngeal (27.45%), oropharyngeal (66.39%), and hypopharyngeal (52.48%) volumes. Furthermore, for every millimeter anterior movement, oropharyngeal volume increased by  $2319.2 \pm 771.8$  mm<sup>3</sup>. Bimaxillary advancement showed a greater increase than isolated maxillary and mandibular advancement in all pharyngeal compartments. Every millimeter of advancement in the bimaxillary group led to a significant increase in oropharyngeal volume, while every millimeter downward movement showed a significant increase in nasopharyngeal volume.

Key words: CBCT; airway compartments; orthognathic surgery; advancement.

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Surgical movement of the maxilla and mandible to correct dentofacial deformities will affect the position of the musculature and soft tissue attached to these structures. The position and tension of the tongue, lips, soft palate, and hyoid bone will inevitably change as their associated skeletal structures are moved, and this may impact the nasal cavity, oral cavity, and the pharyngeal airway volume and shape<sup>1</sup>.

Mandibular setback surgery to address the class III skeletal discrepancies may cause a significant reduction in the oropharyngeal airway dimensions, increasing the propensity for development of breathing disorders<sup>2-4</sup>. This effect has also been seen in cases where maxillary advancement is performed in conjunction with mandibular setback, making isolated maxillary advancement surgery a more acceptable alternative in recent years in order to prevent compromising the pharyngeal airway<sup>5-8</sup>. Mandibular advancement via bilateral sagittal split osteotomies (BSSO) and bimaxillary advancement surgery are recommended for the correction of class II skeletal problems caused by mandibular or bimaxillary retrognathism<sup>9-11</sup>. It has also been shown that advancement of the jaws can significantly improve oropharyngeal dimensions of the airway and effectively treat obstructive sleep apnea (OSA)<sup>12-14</sup>.

Several studies have assessed the airway on two-dimensional cephalometric radiographs<sup>3,12,15,16</sup>. Findings from these studies are limited to linear measurements of sagittal or transverse aspects and cannot accurately represent the morphology of the airway or the compromised areas leading to breathing disorders. Cone beam computed tomography (CBCT) is a reliable and effective technique to quantitatively evaluate the volume and cross-sectional areas of the airway<sup>17,18</sup>. It incurs lower cost and lower radiation exposure on the patient compared with spiral CT<sup>19</sup>. This three-dimensional imaging technique, along with computer software capable of rendering volumetric data and segmenting different areas of the airway, helps clinicians and researchers evaluate changes in the airway that occur in response to orthodontic<sup>20</sup> and orthognathic treatment<sup>21,22</sup> and impact breathing quality<sup>23,24</sup>.

In recent years, several studies have looked into the effects of advancement surgeries on the airway<sup>21,22,25-27</sup>. Some have attempted to assess the impact of bimaxillary advancement or isolated mandibular advancement on different compartments of the upper airway<sup>26,27</sup>. Others have evaluated the change in total

volume in response to single-jaw or bimaxillary advancement surgeries<sup>21,22,25</sup>.

The objective of this project was to evaluate longitudinal changes in volume and minimum cross-sectional area of different compartments of the upper airway (nasal cavity, nasopharyngeal, oropharyngeal, and hypopharyngeal segments) in response to maxillary advancement, mandibular advancement, and bimaxillary advancement surgeries.

## Materials and methods

This was a retrospective cohort study approved by the Boston University Institutional Review Board that included pre- and post-surgical CBCT scans of patients who had received combined orthognathic surgery and orthodontic treatment between 2012 and 2015. A de-identified repository of scans and pertinent coded medical and dental information were screened. Patients with craniofacial anomalies and syndromes of the head and neck area or history of previous orthognathic surgery and/or adenotonsillectomy were excluded. Incomplete and low-resolution scans were eliminated. All patients were post pubertal at the time of surgery as determined by cervical vertebral maturation staging<sup>28</sup>.

An initial screening of the database yielded a sample of 87 patients. After reviewing the available scans and pertinent medical history of the subjects, only 36 scans (58.3% female, 41.7% male) were eligible for inclusion in the study. The sample was divided into three groups based on the type of surgery performed: maxillary advancement ( $n = 11$ ), mandibular advancement ( $n = 12$ ), and bimaxillary advancement with or without genioplasty ( $n = 13$ ). Four of the 13 subjects in the bimaxillary advancement group had an additional genioplasty procedure performed. The mean age at the time of surgery was  $26.6 \pm 12.5$  years. The CBCT images were obtained using the same iCAT machine (Imaging Sciences International, Hatfield, PA, USA) before ( $17.8 \pm 12.3$  months) and after surgery ( $7.8 \pm 7.5$  months). The machine was operated at 120 kVcp, 5 mA, and 0.5 mm nominal focal spot size, rendering a 17.0 cm  $\times$  23 cm field of view with a 0.3-mm voxel size image. Patients were instructed to hold their heads in natural head position and avoid swallowing.

All CBCT images were exported as DICOM extension files (Digital Imaging and Communications in Medicine) and were processed and segmented by the same operator (BK) using Mimics v.18 software (Materialise, Leuven, Belgium).

Soft and hard tissue masks were created for landmark placement and plane construction by one operator (GP). Each hard and soft tissue landmark was digitized on its appropriate mask and verified on axial, sagittal, and coronal slices (Table 1). Using these three-dimensional landmarks, several reference planes and dissector planes were constructed. Axial and coronal reference planes were used to measure the amount and direction of anteroposterior and vertical surgical movement of each landmark (Fig. 1A). Dissector planes were constructed to segment the airway into four compartments: nasal cavity (NC), nasopharynx (NP), oropharynx (OP), and hypopharynx (HP) (Fig. 1B). Basion plane delineated the superior border of the nasal cavity and nasopharynx. The posterior nasal spine (PNS) plane marked the inferior border of these two compartments. Pronasale plane was used as the most antero-inferior border of the nasal cavity. The PNS vertical plane separated nasal cavity and nasopharyngeal volumes. C3 plane separated oropharyngeal and hypopharyngeal volumes, and C4 plane demarcated the inferior border of the hypopharynx. Scans of six subjects were short of C4 plane; therefore the changes in hypopharyngeal volume could not be reported for those images. The minimum cross-sectional area of the pharyngeal airway was measured using InVivo 5.2 software (Anatomage Inc., San Jose, CA, USA). This measurement was depicted as the narrowest area of the airway between PNS plane and C4 plane on the axial slice.

Using a random sample (10% of the original sample), one examiner (GP) performed two separate measurements, 4 weeks apart. The inter-class correlation (ICC) and paired *t*-test were used to examine intra-examiner reliability. For all measurements, the ICC values were  $>0.90$  and no measurement was found to be significantly different at the  $P < 0.05$  level.

The Kolmogorov–Smirnov and Shapiro–Wilk tests were used to test the normal distribution of the data and confirmed that the data had a normal distribution. A paired *t*-test was used to compare the before (T1) and after (T2) linear measurements and the airway volume change for each surgical group (i.e., stratified analysis). The mean percentage change per subject in each airway volume and in minimum cross-sectional area by surgical modality was calculated and then averaged across all subjects. Stepwise multivariate linear regression models were used to predict the effect of the linear

Table 1. Landmarks.

Landmark	Description
Alare (right and left)	The most lateral point on each alar contour
Pronasale	The most anterior midpoint of the nasal tip
B point	The point of maximum concavity in the midline of the alveolar process of the mandible
Genial tubercle	The tip of the projection in the midline of the posterior surface of the body of the mandible
Lingula (right and left)	The projection of bone that forms the mesial boundary of the mandibular foramen
Mental foramen (right and left)	Most superior point on the mental foramina
Menton	The most inferior midpoint of the chin on the outline of the mandibular symphysis
Posterior nasal spine (PNS)	The most posterior midpoint of the posterior nasal spine of the palatine bone
Greater palatine foramen (right and left)	The most anterior point on the greater palatine foramina
Incisive foramen	The most anterior point on the incisive foramen
Nasion	The midpoint of the frontonasal suture
Sella	The center of the hypophyseal fossa (sella turcica)
Piriform aperture points (right and left)	The point on the widest part of the piriform aperture
Infraorbital foramen (right and left)	The most superior point on infraorbital foramina
Zygomatocotemporal suture inferior (right and left)	Most inferior point on the zygomatocotemporal sutures
Basion	The most anterior point of foramen magnum
Porion (right and left)	The most superior point of each external acoustic meatus
C3	The most anterior and inferior point on C3
C4	The most anterior and inferior point on C4

surgical movement on the airway volumetric changes. Statistical significance was evaluated at the 0.05 level. All statistical analyses were performed using SAS 9.4 (SAS Institute, Cary, NC, USA).

## Results

Mean anterior and vertical movements of landmarks for the maxillary, mandibular, and bimaxillary advancement groups are

shown in Table 2. For maxillary advancement, anterior movement of the greater palatine foramina, incisive foramen, and PNS were statistically significant ( $P < 0.05$ ), while these landmarks did not show a significant change vertically. For the mandibular advancement group, anterior movements of all landmarks (B point, genial tubercle, menton, mental foramina, and lingula) were statistically significant ( $P < 0.05$ ), as were vertical

movements, except for lingula. For the bimaxillary advancement group, anterior movements of all mandibular and maxillary landmarks were significant ( $P < 0.05$ ). However, their vertical positions did not change significantly. Transverse movements of the greater palatine foramina did not show a significant difference pre- and post-surgically for the maxillary advancement and bimaxillary advancement groups.

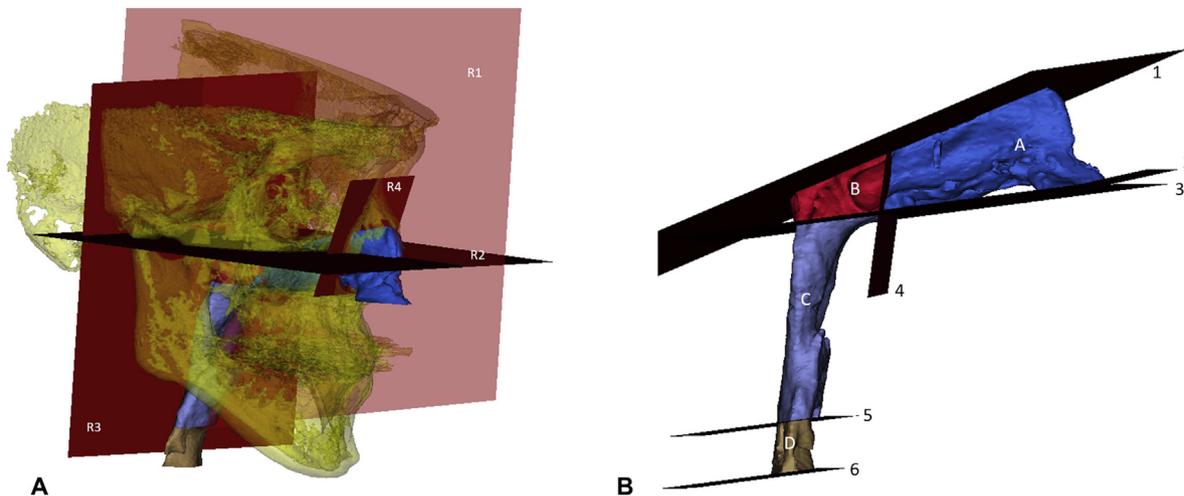


Fig. 1. (A) Reference planes. R1 is the midsagittal plane, i.e. the plane passing through nasion and sella, perpendicular to the Frankfort derivative plane. R2 is the Frankfort derivative plane, i.e. the plane passing through right and left infraorbital foramina and the most inferior point on the zygomatocotemporal suture. R3 is the coronal plane, i.e. the plane passing through basion and perpendicular to the midsagittal and Frankfort derivative planes. R4 is the vertical nasal plane, i.e. the plane passing through nasion and the right and left piriform apertures. (B) Upper airway compartments segmented by dissector planes. A: nasal cavity, B: nasopharyngeal volume, C: oropharyngeal volume, D: hypopharyngeal volume. Dissector planes: '1' is the basion plane, i.e. the plane passing through basion and parallel to the plane passing through nasion and right and left porions; '2' is the pronasale plane, i.e. the plane passing through pronasale and right and left ala nasi; '3' is the PNS plane, i.e. the plane passing through the posterior nasal spine and parallel to the Frankfort derivative plane; '4' is the PNS vertical, i.e. the plane passing through posterior nasal spine and parallel to the vertical nasal plane; '5' is the C3 plane, i.e. the plane passing through the most anterior inferior point on C3 and parallel to the Frankfort derivative plane; '6' is the C4 plane, i.e. the plane passing through the most anterior inferior point on C4 and parallel to the Frankfort derivative plane.

Table 2. Descriptive characteristics of the linear measurements for maxillary, mandibular, and bimaxillary advancement surgeries.

	T1	T2	T2-T1
	Mean $\pm$ SD (mm)	Mean $\pm$ SD (mm)	Mean difference (mm)
<b>Maxillary advancement</b>			
Greater palatine right-coronal plane*	46.3 $\pm$ 9.1	49.9 $\pm$ 10.8	3.7 $\pm$ 3.6
Greater palatine left-coronal plane*	49.4 $\pm$ 3.9	53.9 $\pm$ 2.2	4.5 $\pm$ 3.7
Greater palatine right-FD plane	15.1 $\pm$ 3.2	13.9 $\pm$ 3.3	-1.1 $\pm$ 1.8
Greater palatine left-FD plane	17.6 $\pm$ 7.6	17.3 $\pm$ 10.0	-0.2 $\pm$ 3.3
Incisive foramen-coronal plane*	76.1 $\pm$ 19.5	80.1 $\pm$ 21.12	4.0 $\pm$ 2.2
Incisive foramen-FD plane	32.0 $\pm$ 16.9	32.4 $\pm$ 19.2	0.3 $\pm$ 3.5
PNS-coronal plane*	37.2 $\pm$ 11.5	41.7 $\pm$ 13.0	4.5 $\pm$ 2.4
PNS-FD plane	17.4 $\pm$ 7.9	16.7 $\pm$ 9.9	-0.7 $\pm$ 2.6
<b>Mandibular advancement</b>			
B point-coronal plane*	83.0 $\pm$ 4.3	86.8 $\pm$ 3.9	3.8 $\pm$ 1.6
B point-FD plane*	55.2 $\pm$ 4.7	57.1 $\pm$ 4.2	1.9 $\pm$ 2.4
Genial tubercle-coronal plane*	69.8 $\pm$ 4.5	73.6 $\pm$ 4.4	3.8 $\pm$ 1.9
Genial tubercle-FD plane*	66.5 $\pm$ 4.1	68.1 $\pm$ 4.1	1.6 $\pm$ 1.4
Menton-coronal plane*	70.7 $\pm$ 5.1	74.6 $\pm$ 4.5	3.9 $\pm$ 1.9
Menton-FD plane*	58.8 $\pm$ 4.4	60.7 $\pm$ 3.9	2.0 $\pm$ 1.1
Mental foramen right-coronal plane*	70.7 $\pm$ 5.1	74.6 $\pm$ 4.9	3.9 $\pm$ 1.9
Mental foramen right-FD plane*	58.8 $\pm$ 4.4	60.7 $\pm$ 3.9	2.0 $\pm$ 1.1
Mental foramen left-coronal plane*	70.1 $\pm$ 5.2	73.8 $\pm$ 5.1	3.7 $\pm$ 1.6
Mental foramen left-FD plane*	25.4 $\pm$ 3.6	28.4 $\pm$ 3.4	3.0 $\pm$ 2.3
Lingula right-coronal plane*	25.1 $\pm$ 2.6	27.7 $\pm$ 2.9	2.6 $\pm$ 2.4
Lingula left-coronal plane*	59.3 $\pm$ 5.1	61.3 $\pm$ 4.8	2.1 $\pm$ 1.0
Lingula right-FD plane	24.9 $\pm$ 3.7	25.4 $\pm$ 3.8	0.5 $\pm$ 3.5
Lingula left-FD plane	25.2 $\pm$ 6.3	25.7 $\pm$ 5.9	0.6 $\pm$ 2.9
<b>Bimaxillary advancement</b>			
Greater palatine right-coronal plane*	49.1 $\pm$ 3.9	53.8 $\pm$ 4.3	4.7 $\pm$ 1.8
Greater palatine left-coronal plane*	48.7 $\pm$ 4.3	53.4 $\pm$ 4.1	4.7 $\pm$ 2.1
Greater palatine right-FD plane	17.8 $\pm$ 3.6	17.9 $\pm$ 4.0	0.1 $\pm$ 2.3
Greater palatine left-FD plane	18.0 $\pm$ 3.2	18.0 $\pm$ 3.6	-0.02 $\pm$ 2.2
Incisive foramen-coronal plane*	81.2 $\pm$ 5.5	86.3 $\pm$ 5.1	5.1 $\pm$ 1.3
Incisive foramen-FD plane	29.7 $\pm$ 3.9	29.1 $\pm$ 4.1	-0.6 $\pm$ 2.6
PNS-coronal plane*	40.3 $\pm$ 3.7	45.1 $\pm$ 3.4	4.7 $\pm$ 1.4
PNS-FD plane	17.4 $\pm$ 4.3	18.0 $\pm$ 4.5	0.6 $\pm$ 2.5
B point-coronal plane*	81.5 $\pm$ 8.5	88.0 $\pm$ 7.5	6.4 $\pm$ 3.1
B point-FD plane	63.2 $\pm$ 4.4	61.5 $\pm$ 6.0	-1.7 $\pm$ 3.6
Genial tubercle-coronal plane*	67.9 $\pm$ 9.7	76.0 $\pm$ 8.2	8.1 $\pm$ 4.3
Genial tubercle-FD plane	72.9 $\pm$ 5.2	74.1 $\pm$ 5.9	1.3 $\pm$ 4.1
Menton-coronal plane*	76.5 $\pm$ 11.1	85.5 $\pm$ 9.7	9.1 $\pm$ 4.8
Menton-FD plane	84.5 $\pm$ 6.4	85.3 $\pm$ 6.9	0.8 $\pm$ 4.2
Mental foramen right-coronal plane*	68.5 $\pm$ 8.6	74.7 $\pm$ 7.3	6.2 $\pm$ 3.4
Mental foramen right-FD plane	64.1 $\pm$ 5.2	64.8 $\pm$ 5.6	0.7 $\pm$ 3.5
Mental foramen left-coronal plane*	67.9 $\pm$ 8.5	74.4 $\pm$ 8.0	6.5 $\pm$ 3.6
Mental foramen left-FD plane	64.8 $\pm$ 5.8	65.3 $\pm$ 5.3	0.5 $\pm$ 2.9
Lingula right-coronal plane*	25.0 $\pm$ 4.3	27.9 $\pm$ 4.5	2.9 $\pm$ 2.4
Lingula left-coronal plane*	24.7 $\pm$ 4.6	28.1 $\pm$ 5.1	3.4 $\pm$ 1.8
Lingula right-FD plane	26.7 $\pm$ 4.6	27.0 $\pm$ 3.7	0.3 $\pm$ 3.2
Lingula left-FD plane	26.5 $\pm$ 4.8	25.6 $\pm$ 3.4	-0.9 $\pm$ 3.9

FD, Frankfort derivative; PNS, posterior nasal spine; SD, standard deviation.

\* $P$ -value < 0.05.

In the maxillary advancement group, 4.0  $\pm$  2.2 mm anterior movement of the incisive foramen led to a significant increase of 41.40% ( $P = 0.003$ ) in oropharyngeal volume, while the nasal cavity, nasopharyngeal and hypopharyngeal airways did not show any significant increase. In the mandibular advancement group, 3.8  $\pm$  1.6 mm anterior movement of B point caused a significant increase of 21.17% ( $P = 0.0005$ ) in the oropharyngeal volume. The bimaxillary advancement group showed a significant increase in

volume of nasopharyngeal, oropharyngeal, and hypopharyngeal cavities by 27.45% ( $P = 0.01$ ), 66.39% ( $P = 0.0001$ ), and 52.48% ( $P = 0.01$ ), respectively, in response to 5.1  $\pm$  1.3 mm anterior movement of incisive foramen and 6.4  $\pm$  3.1 mm anterior movement of B point (Table 3).

The minimum cross-sectional area of the oropharyngeal region increased significantly for all three groups: maxillary advancement by 61.3 mm<sup>2</sup> ( $P = 0.015$ ), mandibular advancement by 51.1 mm<sup>2</sup> ( $P = 0.0004$ ),

and bimaxillary advancement by 117.1 mm<sup>2</sup> ( $P = 0.0003$ ) (Table 4).

Linear regression models for the single-jaw advancement groups did not show any statistically significant results. However, in the bimaxillary advancement group, when controlling for the vertical movement of the greater palatine foramen and vertical and sagittal movements of menton, the multivariate regression analysis showed that every 1 mm anterior movement of the greater palatine foramen led to a significant increase of 2319.2 mm<sup>3</sup>

Table 3. Paired *t*-test for airway volume changes after advancement surgeries.

	T1 Mean ± SD (mm <sup>3</sup> )	T2 Mean ± SD (mm <sup>3</sup> )	T2-T1 MD (mm <sup>3</sup> )	95% CI	Percentage change	<i>P</i> -value
Maxillary advancement						
Nasal cavity	9688.0 ± 3058.5	10,293.8 ± 2168.22	605.8	-1168.9 to 2380.5	13.14%	0.5
Nasopharyngeal cavity	4479.1 ± 2007.8	5027.6 ± 2318.8	548.5	-339.8 to 1436.8	17.84%	0.2
Oropharyngeal cavity*	14,984.6 ± 4417.3	20,484.2 ± 5968.6	5499.7	2445.2 to 8554.2	41.40%	0.003
Hypopharyngeal cavity	4794.2 ± 3007.4	6782.4 ± 3520.7	891.7	-441.1 to 2224.6	33.90%	0.16
Mandibular advancement						
Nasal cavity	11,165.8 ± 2165.8	10,935.8 ± 2371.2	-230.1	-1726.7 to 1266.5	-0.43%	0.7
Nasopharyngeal cavity	6256.4 ± 1779.2	6356.8 ± 2016.1	100.5	-621.3 to 822.2	2.19%	0.8
Oropharyngeal cavity*	15,585.4 ± 6605.7	18,075.9 ± 6841.8	2490.4	1356.9 to 3624	21.17%	0.0005
Hypopharyngeal cavity	4747.9 ± 1853.0	5474.0 ± 2618.5	726.1	-645.7 to 2097.9	17.16%	0.3
Bimaxillary advancement						
Nasal cavity	10,611.2 ± 3262.7	12,401.0 ± 2981.7	1789.8	-105.9 to 3685.6	23.12%	0.06
Nasopharyngeal cavity*	5690.7 ± 2564.6	7055.3 ± 3382.7	1364.6	321.6 to 2407.7	27.45%	0.01
Oropharyngeal cavity*	12,917.2 ± 3126.0	20,914.1 ± 5966.1	7996.9	4848.5 to 11,145.3	66.39%	0.0001
Hypopharyngeal cavity*	4794.2 ± 3007.4	6782.4 ± 3520.7	1988.2	604.7 to 3371.6	52.48%	0.01

CI, confidence interval; MD, mean difference; SD, standard deviation.

\**P*-value < 0.05.

Table 4. Paired *t*-test for minimum cross-sectional area change after each surgery.

Type of surgery	T1 Mean ± SD (mm <sup>2</sup> )	T2 Mean ± SD (mm <sup>2</sup> )	T2-T1 MD (mm <sup>2</sup> )	95% CI	Percentage change	<i>P</i> -value
Bimaxillary advancement*	101.6 ± 46.8	218.7 ± 113.1	117.1	65.4 to 168.7	143.35%	0.0003
Mandibular advancement*	150.7 ± 76.1	201.7 ± 88.2	51.1	28.5 to 73.6	49.28%	0.0004
Maxillary advancement*	130.1 ± 50.7	191.4 ± 69.6	61.3	15.0 to 107.5	76.80%	0.015

CI, confidence interval; MD, mean difference; SD, standard deviation

\**P*-value < 0.05.

(standard error 771.8) in the oropharyngeal cavity. In addition, when controlling for the anterior movement of PNS and anterior and vertical movements of genial tubercle, incisive foramen, and menton, for every 1 millimeter downward movement of PNS, a significant increase of 1105.1 mm<sup>3</sup> (standard error 339.3) in the nasopharyngeal cavity was observed (Table 5).

## Discussion

This was a retrospective study designed to evaluate changes in four airway compartments in response to three different advancement surgeries using available

CBCT scans of orthognathic patients. The data from male and female subjects were pooled since there was no significant difference between the two groups, as also suggested in other studies<sup>4,5</sup>.

The results of this study showed that advancement of the maxilla or mandible alone or in combination did not have a significant effect on the volume of the nasal cavity. This was to be expected in the study sample, where the transverse movement of the greater palatine foramina was shown not to be significant. Perhaps if the maxilla had been expanded surgically, the volume of the nasal cavity may have demonstrated an increase<sup>29</sup>. In this study, isolated mandib-

ular advancement and isolated maxillary advancement led to a significant increase in oropharyngeal volume. The findings also indicated that the impact of similar amounts of advancement of maxilla and mandible, as seen in Table 2, was more pronounced for isolated maxillary advancement surgery. When the two surgical modalities were combined in the bimaxillary advancement group, the increase in airway volume extended to the hypopharyngeal airway and the effect on nasopharyngeal and oropharyngeal compartments was more pronounced than with one-jaw advancement surgeries. In this sample, the mean anterior movements of maxillary landmarks were larg-

Table 5. Multivariate regression analysis of the association between airway volume and linear surgical movements for bimaxillary advancement surgery.

Outcome	Predictor	Beta estimate (mm <sup>3</sup> )	SE	95% CI
Oropharyngeal cavity <sup>a</sup>	Greater palatine foramen Anterior movement	2319.2	771.8	539.5 to 4098.9
Nasopharyngeal cavity <sup>b</sup>	PNS Vertical movement	1105.1	339.3	163.0 to 2047.1

CI, confidence interval; PNS, posterior nasal spine; SE, standard error.

<sup>a</sup>Controlling for menton anterior, menton vertical, and greater palatine left vertical movements.

<sup>b</sup>Controlling for genial tubercle anterior, menton anterior, incisive foramen anterior, PNS anterior, menton vertical, genial tubercle vertical, and incisive foramen vertical movements.

er in the bimaxillary advancement group than in the maxillary advancement group. This was also true for mandibular landmarks when comparing the mandibular advancement group to the bimaxillary advancement group. This difference was especially noticeable for genial tubercle and menton, which could be attributed to the additional genioplasty procedure performed on four subjects in the bimaxillary advancement group. The four subjects who received a genioplasty in conjunction with bimaxillary advancement were not analyzed as a separate group due to the small sample size.

Hernandez-Alfaro et al.<sup>22</sup> reported a significant volume increase in the upper airway (corresponding to oropharyngeal compartment) of 30 patients in response to maxillary, mandibular, and bimaxillary advancement surgeries. The amount of increase in volume of the oropharyngeal area in the maxillary advancement group in the present study is in agreement with the amount reported by the authors for their maxillary advancement sample, but the amount varied significantly for the mandibular advancement groups. This discrepancy in findings may be due to differences in amount of advancement, which was not reported by the authors. Kochel et al.<sup>26</sup> and Dalla Torre et al.<sup>30</sup> showed an increase in the total pharyngeal volume in response to isolated mandibular advancement (by 32% and 73%, respectively). The difference between the present study results and those of these previously reported studies could be due to the smaller sample size of the present study or the difference in amounts of advancement, which were also not reported by the authors.

Valladares-Neto et al.<sup>25</sup> reported that mandibular advancement ranging from 4 mm to 10 mm with minimal maxillary advancement increased the total volume of the pharyngeal airway by 54.5%. Another retrospective study showing bimaxillary advancements of 10–18 mm found an average increase of 56% in pharyngeal airway volume<sup>21</sup>. This is comparable to the present study finding of a 66.39% increase in oropharyngeal volume in response to a  $5.1 \pm 1.3$  mm advancement at incisive foramen and a  $6.4 \pm 3.1$  mm advancement at B point. In contrast, Schendel et al.<sup>31</sup> reported a volume increase of 237% in the upper airway space in 10 patients in response to a mean bimaxillary advancement of approximately 9.5 mm and an additional average genioglossal movement of 6 mm in selected cases. This increase is significantly larger than the

current study as well as others, which may be explained by their larger surgical movement and small sample size. Zinser et al.<sup>27</sup> looked at four different compartments of the airway in response to bimaxillary advancement for OSA patients. They found a similar amount of increase in the pharyngeal airway but reported the largest increase of the airway space for the nasal cavity, while the present study did not find a significant increase in that segment. This may be due to an additional septoplasty and inferior turbinate reduction performed in some of their patients that would have contributed to the enlargement of the nasal cavity volume for that study.

The increase in minimum cross-sectional area of the pharyngeal airway in response to surgical movements was most significant for bimaxillary advancement, followed by isolated maxillary advancement and isolated mandibular advancement, which had the least impact. Bimaxillary advancement allowed for larger amounts of horizontal movement of maxilla and mandible and led to the most significant increase in minimum cross-sectional area. This is particularly noteworthy, since an increase in the minimum cross-sectional area may have a more significant impact on breathing quality than the mere increase in volume of the airway<sup>32</sup>. The closest report to the study finding of a 143.35% increase in minimum cross-sectional area in response to bimaxillary advancement is that of Raffaini and Pisani<sup>21</sup>, who showed a 112% increase. Valladares-Neto et al.<sup>25</sup> reported an enlargement of 79.7% in response to bimaxillary advancement. However, their report indicated that this movement was largely due to mandibular advancement with only minimal maxillary advancement, which may explain the lesser amount of increase.

It appears that there is only one other study that has explored correlations between the extent of surgical movements and changes in airway volume<sup>33</sup>. Chang et al.<sup>33</sup> found that up to 7 mm advancement of maxilla led to an increase in nasopharyngeal airway volume, but any advancement beyond this point did not result in a further increase in airway volume. They likewise did not find a significant correlation between the amount of advancement or setback of the mandible and the change in pharyngeal volume. In the present study, multivariate regression analysis of the association between airway volume and linear surgical movements for

bimaxillary advancement showed that 1 mm anterior movement of the greater palatine foramen increased the oropharyngeal airway volume by 2319.2 mm<sup>3</sup>. This is particularly important since anterior movement of maxillary landmarks is shown to significantly affect the volume of the oropharyngeal airway. One millimeter downward movement of PNS led to an increase of 1105.1 mm<sup>3</sup> (standard error 339.3) in the nasopharyngeal cavity. The same regression analysis did not detect similar associations between the movement of landmarks in the isolated maxillary and mandibular advancement groups and the change in airway volume; perhaps this may have been possible with larger surgical movements. The discrepancy between these findings may be attributed to the difference in amounts of surgical movements and to the fact that polynomial regression models have limitations that include poor interpolatory, extrapolatory, and asymptotic properties with a high bias-variance tradeoff.

Bimaxillary advancement surgery has been proposed to be an effective procedure for the treatment of OSA as it has been shown to successfully increase the volume and cross-sectional area of the pharyngeal airway<sup>31,34</sup>. Even though one of the limitations of this retrospective study is the failure to screen for sleep disordered breathing during the pre-surgical work-up and post-surgical evaluation of patients, the results showing a significant increase in the airway imply that the surgical modalities assessed in this study may help improve OSA symptoms.

In conclusion, all three advancement procedures increased the oropharyngeal airway volume significantly. Nasopharyngeal, oropharyngeal, and hypopharyngeal airway volumes responded in varying degrees to the different advancement surgeries. Isolated maxillary advancement and isolated mandibular advancement increased oropharyngeal volume significantly. In addition, the impact of comparable amounts of advancement of the maxilla and mandible was more noticeable for isolated maxillary advancement surgery. Bimaxillary advancement showed a more pronounced increase in pharyngeal compartments than the isolated maxillary and mandibular advancement surgeries. Every millimeter of advancement in the bimaxillary surgical group led to a significant increase in oropharyngeal volume, while every millimeter downward movement of PNS showed a significant increase in nasopharyngeal airway volume.

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