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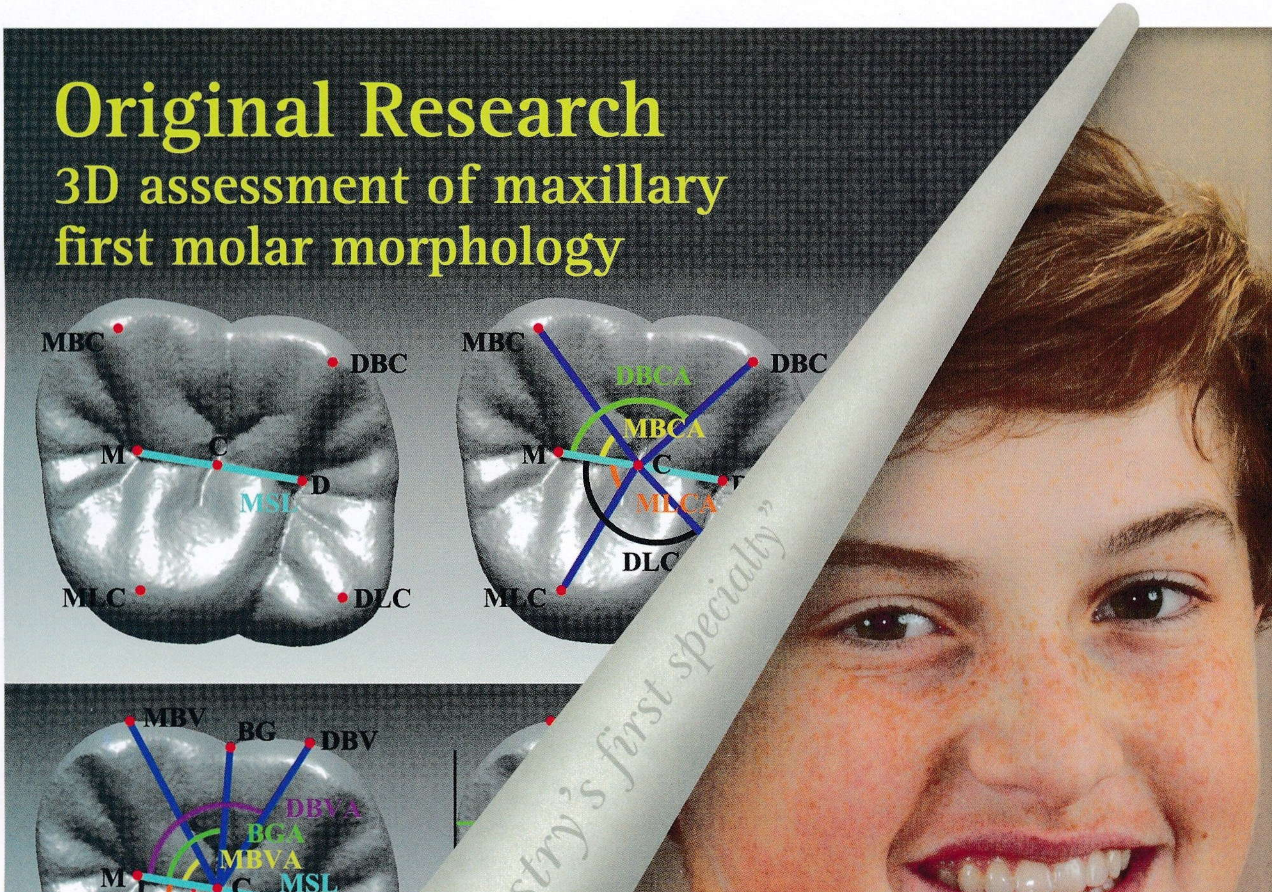

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Three-dimensional upper-airway changes with maxillomandibular advancement for obstructive sleep apnea treatment

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Introduction: Airway size increases are associated with maxillomandibular advancement (MMA) surgery and improvement or elimination of obstructive sleep apnea (OSA). The 3-dimensional morphologic, volumetric, height, cross-sectional surface area, and diameter changes of the upper airway in patients with OSA after MMA, however, are not well understood. **Methods:** Patients with moderate or severe OSA who underwent MMA surgery were evaluated by preoperative and postoperative cone-beam computed tomography scans and polysomnograms. The upper airway space was also divided into retropalatal and retroglossal spaces and was analyzed for volumetric, height, cross-sectional surface area, transverse, and anteroposterior diameter changes. **Results:** Ten consecutive OSA patients with an average preoperative apnea/hypopnea index of 46 and treated with MMA surgery were included in this study. There were 8 men and 2 women, with an average age of 46 years and an average body mass index of 28. There was an average of a 2.5-fold increase in the total volume of the upper airway space. The retropalatal space increased by 3.5-fold. The retroglossal space increased by 1.5-fold. The greatest change in a cross-sectional area occurred in the transverse axis in both the retroglossal and retropalatal spaces. The average apnea/hypopnea index was 4 postoperatively. **Conclusion:** MMA surgery results in a significant increase in the volume and a morphologic airway change from a round to an elliptical f shape in the upper airway space in patients with OSA. The combination of these actions reduces the collapsibility of the upper airway space, hence improving or resolving the OSA. (Am J Orthod Dentofacial Orthop 2014;146:385-93)

Obstructive sleep apnea (OSA) is a disease of abnormal upper airway anatomy. A small upper airway can be caused by the relative positions of the maxillofacial skeletal structures and of the dental arches to one another and to the cranial base. An upper airway size of about 40 to 67.1 mm^2 at the smallest cross-sectional area in adults has been shown to be associated with sleep apnea.[1,2] This is in comparison with an area of 149.3 mm^2 in normal adults.[1-3] The position, size, and degree of oropharyngeal soft-tissue collapse during deep stages of sleep affect the upper airway, and this is also influenced by the body mass index.[4,5] Treating patients successfully with OSA remains a challenge among all dental and medical specialists. Continuous positive airway pressure (CPAP) therapy is still prescribed as the first line of therapy and considered the gold standard in the treatment of OSA patients. However, CPAP therapy has compliance limitations, and patients still seek alternative treatment options, including upper airway surgery.[6] However, we lack rigorous data on the outcomes of surgical management of OSA patients, high-level controlled studies in the medical literature, and standardized criteria to define surgical success.[4,7] Shortcomings described in the systematic review and meta-analysis by Caples et al[4] were inconsistent data in preoperative imaging as well as evaluations of the upper airway. There is also an absence of systematic reviews of cone-beam computed tomography (CBCT) imaging and validation of the analysis methodology of the upper airway in OSA patients in the peer-reviewed literature.[8]

CBCT has revolutionized the field of maxillofacial surgery. It has allowed for the accurate visualization of upper airway anatomic regions in 3-dimensional (3D) and

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2-dimensional patterns, reduced the amount of exposed ionizing radiation, and provided the immediate convenience of an in-office imaging system.[4-8] This has aided practitioners in the diagnosis, treatment planning, outcome assessment of surgery, and education of patients regarding their condition. CBCT has been used to evaluate the upper airway anatomy in many software programs. Some of the computer viewing software programs showed high correlations but are inaccurate in the measurement of the upper airway volume.[9] Today, the only commercially available software viewer program that has been shown to be accurate and reliable for measuring the upper airway volume is the 3dMDVultus software (3dMD, Atlanta, Ga).[10,11] Total airway volume and smallest airway area have also been shown to correlate with the severity of OSA.[1,2,13-15]

At the present time, maxillomandibular advancement (MMA) remains the most effective surgical procedure in treating patients with moderate to severe OSA,[5,16-21] although only 1 study has been assigned a level of 1b in a systematic literature search.[22] Advancement of maxillofacial skeletal structures opens the oropharyngeal airway and places the oropharyngeal musculature on tension, although these changes are still not well understood in 3 dimensions. These changes are stated to reduce the collapsibility of the upper airway during deep stages of sleep. It has been shown in the peer-reviewed literature that the success rates are as high as into the 90th percentile.[5]

The aim of this study was to analyze the morphologic, volumetric, height, cross-sectional surface area, and diameter changes of the upper airway in a systematic fashion in patients with OSA before and after MMA surgery. Understanding the pathologic anatomy of the upper airway of the OSA patient and how it changes with MMA surgery will aid surgeons and orthodontists in the treatment planning for these patients. We describe in a comprehensive and systematic fashion the evaluation of the upper airway of OSA patients before and after MMA surgery. Our hypothesis was that the advancements of the maxilla and the mandible cause significant increases in the upper airway volume and are associated with improved scores in the polysomnogram (PSG) and other clinical measurements of OSA.

MATERIAL AND METHODS

Patients with proven moderate or severe OSA who underwent MMA surgery were evaluated by preoperative and postoperative CBCT scans and PSGs. The CBCT scans were done on the same scanner in neutral head position while the patients were seated. The DICOM data were then analyzed via the 3dMDVultus software. The study was approved by Stanford University's review board (number 21314). A systematic analysis of the upper airway changes was the performed by comparing the presurgical and postsurgical scans. The upper airway space (UAS) was identified and measured from the level of the posterior nasal spine to the hyoid bone. The UAS was also divided into the retropalatal space (from the level of posterior nasal spine to the lower edge of the soft palate) and the retroglossal space (from the lower edge of the soft palate to the hyoid bone). The UAS was analyzed for volumetric, height, cross-sectional surface area, transverse, and anteroposterior diameter changes.

A diagnosis of OSA was confirmed by overnight polysomnography, and the upper airway was evaluated with nasal endoscopy. Each patient underwent a CBCT scan on the same machine (i-CAT; Imaging Sciences International, Hatfield, Pa), and 3D cephalometric analysis was performed preoperatively on each patient. The patients were in preoperative orthodontic treatment initially for an average of 6 months. The 3dMDVultus software was used for virtual surgical planning to optimize the functional and esthetic results and to perform an automated airway analysis. Dental models were taken, and model surgery was performed, with fabrication of intermediate and final splints. Maxillomandibular advancement was performed on each patient. Genioglossal advancement was also performed when indicated to normalize dentofacial structures and improve procedural outcomes. Septoplasty with inferior turbinate reduction out-fracture was also performed when indicated by a preoperative small nasal airway with turbinate hypertrophy or septa deviation.

In the operating room, under general anesthesia with nasal endotracheal tube and local anesthetic with epinephrine, maxillary LeFort I and mandibular bilateral sagittal split osteotomies were performed. The redundant maxillary, palatine, and vomer bones were harvested and used as bone grafts to the maxilla. The maxilla was mobilized and placed into an intermediate splint and then fixated into the advanced position using rigid plates and screws. When indicated, a septoplasty or partial inferior turbinectomies were performed once the maxilla was down-fractured and before fixation. Next, bilateral sagittal split osteotomies of the mandible were performed. The mandible was advanced into occlusion using a final splint and fixated with rigid plates and screws. When indicated, a genial osteotomy that captured the genial tubercle and the genioglossal muscle was performed; this caused advancement to the desired position that was fixated with rigid plates and screws.

The patients were admitted postoperatively to the surgical intensive care unit for airway observation and medical management. They were then transferred to

Table I. Preoperative and postoperative AHI for each patient undergoing MMA

Patient	*Sex*	*Age (y)*	*BMI*	*Before AHI*	*After AHI*
NB	M	51	27	42	3.8
CD	M	36	30.5	31	0
KG	M	51	29	48	0
RJ	M	35	28	54.6	1.5
SD	M	47	23	18	4
VE	F	49	19.8	53.5	28.4
TM	M	56	29.2	21	5
RC	M	47	35	68	3
NS	M	65	27	77	4
MS	F	62	37	16	2

M, Male; *F*, female.

Table II. Skeletal movement in 10 patients

Patient	*Skeletal pattern*	*Mandibular advancement (mm)*	*Maxillary advancement (mm)*	*Chin advancement (mm)*
NB	II	9	9	8
CD	I	9	9	0
KG	II	9	9	0
RJ	II	12	8	6
SD	II	11	8	0
VE	II	11	10	4
TM	I	11	11	0
RC	II	9	9	0
NS	II	10	8	0
MS	II	6	4	0

the surgical floor on the first postoperative day and discharged once they were tolerating adequate oral intake and oral pain medication. The patients were seen routinely for follow-up by both the surgeon and the orthodontist. Postoperative CBCT scans, upper airway analyses, and PSGs were performed at a minimum of 3 months postoperatively.

Patients with proven moderate to severe OSA who underwent MMA surgery were evaluated by preoperative and postoperative CBCT scans and PSG. The CBCT scans were done in neutral head position on the same scanner by the same operator while the patient was seated. The DICOM data were then analyzed via the 3dMDVultus software. This computer-assisted 3D airway analysis has been previously shown to be accurate and reproducible.[4] A systematic analysis of the upper airway changes was then performed by comparing the presurgical and postsurgical scans. The UAS was identified and measured from the level of the posterior nasal spine to the hyoid bone. The UAS was also divided into retropalatal space (from the level of posterior nasal spine to the lower edge of the soft palate) and retroglossal space (from the lower edge of the soft palate to the hyoid bone). The UAS was analyzed for volumetric, height, cross-sectional surface area, transverse, and anteroposterior diameter changes.

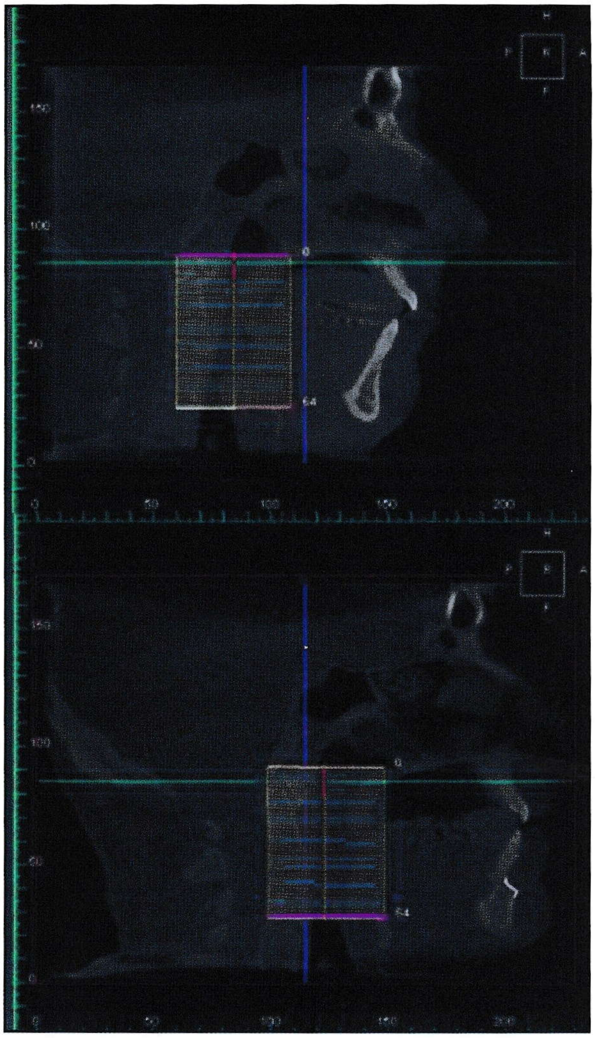

Fig 1. Airway analysis in the lateral view before surgery and after MMA. Note the large increase in airway in this view.

RESULTS

Ten consecutive moderate to severe OSA patients diagnosed by PSG and treated by MMA were included in this study. Average age at surgery was 46.4 years (range, 35-62 years). Eight patients were men, and 2 were women. The preoperative apnea-hypopnea index (AHI) averaged 42 (range, 16-68). An AHI of less than 5 is considered normal (Table I). Preoperative body mass index averaged 28.6. The mean maxillary movement was 9.4 mm, the mean mandibular movement was 9.5 mm, and the average genioglossal movement when performed was 6 mm (Table II). There were no major complications

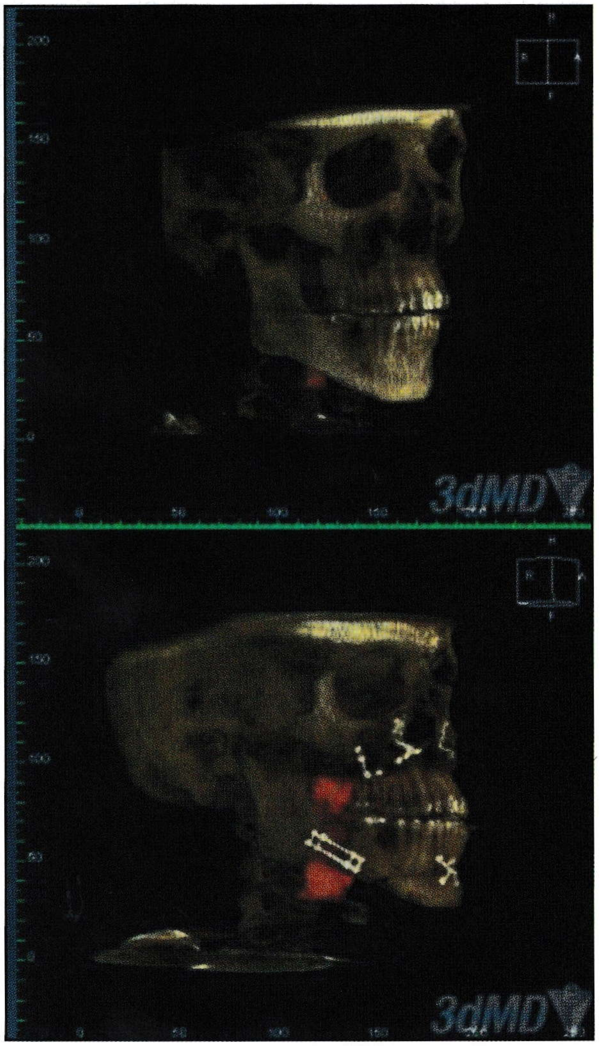

Fig 2. Presurgical and postsurgical views of the patient in Figure 1, showing the MMA and advancement genioplasty.

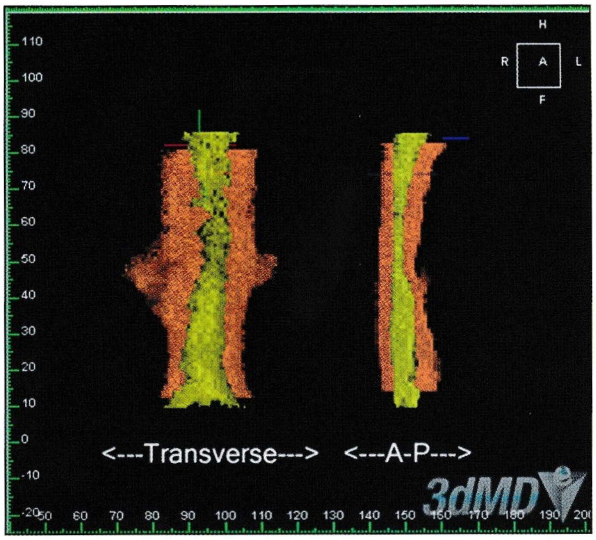

Fig 3. Average presurgical and postsurgical changes in the anteroposterior (*A-P*) and transverse dimensions of the airway. *Yellow*, preoperative; *orange*, postoperative.

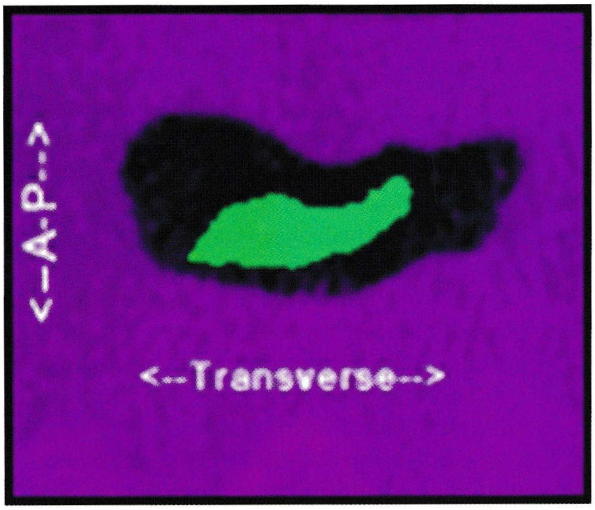

Fig 4. Changes at the smallest average cross-sectional airway with surgery. *Green*, preoperative; *black*, postoperative.

and 2 minor complications: 1 patient had an infection requiring plate removal at a later date, and a second patient had an unfavorable split that was managed intraoperatively, resulting in a complete osteotomy and advancement without adverse consequences.

The volume of the UAS increased significantly by 237% as a result of the maxillomandibular advancement (Figs 1-3). The retropalatal volume increased more than the retroglossal volume, 361% to 165%. The average area of the smallest airway (choke point) before surgery was 74.1 mm^2, and after surgery it was 176.9 mm^2. The surface area at the choke point in the retropalatal space also increased by a greater percentage than did the retroglossal space, 664.22% vs 100.98% (Fig 4). As such, the location of the choke point generally is in the retropalatal space before surgery and in the retroglossal space after surgery. Normalization of the airway refers to the change in shape of the UAS from a funnel shape to a tube-like shape.

Looking more closely at surface-area slices, we found that the transverse dimension increased more than the anteroposterior dimension in millimetric changes (Figs 3 and 4; Tables III-VI). However, the anteroposterior dimension increased more than did the transverse dimension in percentage change; this is because the anteroposterior dimension is generally smaller than the transverse dimension: most airways are spheroid. Thus,

Table III. Average changes in total upper airway volume and at the retropalatal and retroglossal regions

	RPV (cc^3)			RGV (cc^3)		
Change in UAV (%)	Presurgery	Postsurgery	Change in RPV (%)	Presurgery	Postsurgery	Change in RGV (%)
540.60	1.33	8.46	536.09	1.89	13	587.83
35.19	3.97	4.49	13.10	3.59	5.73	59.61
41.72	3.91	5.77	47.57	7.16	10.67	49.02
793.06	1.2	20.56	1613.30	2.26	9.34	313.27
37.97	4.92	8.89	80.69	5.41	5.53	2.22
137.93	7.44	16.04	115.59	4.82	8.02	66.39
72.47	4.7	10.69	127.45	7	12.15	73.57
268	3.4	8.98	264	7.01	15.31	228
270	4.49	9.86	219	6.7	7.66	114
197	6.07	10.36	170	1.91	5.28	276

The average airway volume increased by 237%; the increase was greater in the retropalatal region compared with the retroglossal region, 365% to 164%.
UAV, Upper airway volume; *RPV*, retropalatal volume; *RGV*, retroglossal volume.

Table IV. Cross-sectional views with average changes in area at selected transverse levels of the airway including the smallest cross-sectional airway

Patient	Preoperative smallest RP area (mm^2)	Postoperative smallest RP area (mm^2)	Change (%)	Preoperative smallest RG area (mm^2)	Postoperative smallest RG area (mm^2)	Change (%)	Preoperative smallest area location	Postoperative location of the smallest area
NB	19.7	191.87	873.47	49.68	155.34	212.68	RP	RG
CD	74.52	61.83	−17.03	88.65	116.01	30.86	RP	RP
KG	103.8	158.85	53.03	109.89	152.01	38.33	RP	RG
RJ	8.37	273.5	3167.62	44.28	156.6	253.66	RP	RG
SD	104.84	187.83	79.16	107.46	161.1	49.92	RP	RG
VE	139.7	400.58	186.74	133.65	268.46	100.87	RG	RG
TM	95.36	387.69	306.55	60	72.32	20.53	RG	RG
RC	48.78	395.2	810	121.32	368.45	304	RP	RG
NS	99.63	277.9	228	196.55	183.78	−9	RP	RG
MS	68.85	197.09	286	75.33	188.64	249	RP	RG
	Average % change RP	664.22%						
	Average % change RG	100.98%						
	Preoperative smallest area location	Retropalatal						
	Postoperative location of smallest area	Retroglossal						

The greatest change was retropalatal (*RP*). The choke point, or smallest airway area, changed from a preoperative position of retropalatal to retroglossal (*RG*) postoperatively.

Table V. Average changes in anteroposterior (AP) airway dimensions were 6.40 mm in the retropalatal (RP) region and 2.6 1 mm in the retroglossal (RG) region

Patient	Preoperative RP, AP distance (mm)	Postoperative RP, AP distance (mm)	Difference (mm)	Preoperative RG, AP distance (mm)	Postoperative RG, AP distance (mm)	Difference (mm)
NB	2	5.7	3.7	5.4	6.9	1.5
CD	5.7	6.6	0.9	6	9	3
KG	3	4.5	1.5	6.9	8.7	1.8
RJ	6	25.2	19.2	4.2	6.6	2.4
SD	2.1	6.9	4.8	5.1	6	0.9
VE	4.8	9.6	4.8	3.9	12.6	8.7
TM	4	11.2	7.2	6.4	6.4	0
RC	4.8	15.9	11.1	9.6	17.5	7.9
NS	6.9	14.1	7.2	10.2	6.93	−3.3
MS	3	7.5	4.5	3	15.3	12.3

Table VI. Average changes in the transverse airway dimensions were 11.64 mm in the retropalatal (RP) region and 7.11 mm in the retroglossal (RG) region

Patient	*Preoperative RP, transverse distance (mm)*	*Postoperative RP, transverse distance (mm)*	*Difference (mm)*	*Preoperative RG transverse distance (mm)*	*Postoperative RG transverse distance (mm)*	*Difference (mm)*
NB	8.1	30.6	22.5	10.2	23.4	13.2
CD	16.5	16.8	0.3	19.8	19.2	−0.6
KG	24	29.7	5.7	21.9	27.3	5.4
RJ	1.8	28.2	26.4	12	30	18
SD	28.5	34.8	6.3	23.7	32.4	8.7
VE	26.4	37.5	11.1	26.1	28.8	2.7
TM	22	31.2	9.2	12.4	14.8	2.4
RC	11.4	29.4	13.5	14.7	28.2	13.5
NS	16.8	24.9	8.1	19.8	33	13.2
MS	17.1	28.8	11.7	26.1	24.6	−1.5

The change with MMA was greater in the transverse airway than in the anteroposterior airway (compare Figs 5 and 6).

the airway increases the most in a lateral fashion. The retropalatal space again increased more in both the transverse and anteroposterior dimensions than did the retroglossal space. Two-dimensional cephalometric studies fail to account for the changes in the transverse dimension.

Total height of the airway decreased slightly with surgery but not significantly in this study (Fig 5). The hyoid to mandibular plane measurement decreased with surgery, indicating an elevation of the hyoid. The average hyoid to mandibular plane measurement before surgery was 20.79 mm; in the literature, more than 15 mm is considered abnormal and associated with OSA (Fig 4; Table VII).

The hyoid bone, a predictor of airway obstruction, also changes and moves more superiorly and closer to the mandible (Fig 6; Table VIII).

We believe that the 1 patient with an AHI of 28.4 postoperatively was due to additional complications of several drugs that the patient was taking for other conditions that also affect sleep. The patient was referred for behavioral sleep therapy and sleep hygiene.

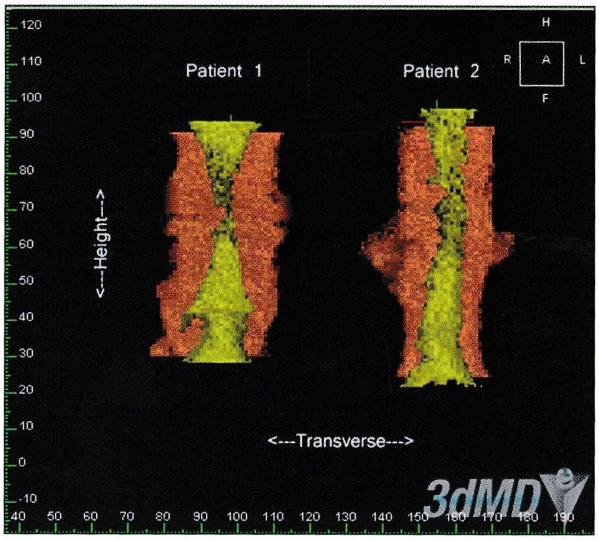

Fig 5. Average horizontal change in the airways before and after surgery. *Yellow*, preoperative; *orange*, postoperative.

DISCUSSION

MMA surgery plays an important role in the correction of OSA that is refractive to medical management, or when medical management is not tolerated, and in patients desiring a definitive correction of the problem. In a recent study, Boyd et al[21] stated that MMA should be the surgical option of choice in patients with moderate or greater OSA. An older adult patient usually requires an advancement of 1 cm based on the common perception and the literature.[16-19] However, few studies of the 3D airway with surgery looked at multiple factors. The widespread use of CBCT scans and the recent development of automated airway analysis systems that have been validated allow the surgeon more refinement in the surgical planning, since exact sites and the extent of the obstruction can be better visualized. Thus, surgery can be tailored for each patient. The upper airways of 10 normal subjects with Class I occlusion were evaluated with CBCT, and the total volumes and smallest cross-sectional surface areas were measured and found to be in the oropharynx.[11] This was a small study, and we did not identify the exact location of the smallest airway area (choke point) in the oropharynx. Recently, the normal morphology, volume, choke point, and growth pattern of the upper airway have been described in the literature by Schendel et al.[3] These authors looked at 1300 normal subjects from 6 to 65 years of age. They identified the upper airway boundaries and volumes in different age

Table VII. The upper airway height generally did not change significantly with surgery

Patient	*Presurgery (mm)*	*Postsurgery (mm)*	*Pre-RP (mm)*	*Post-RP (mm)*	*Pre-RG (mm)*	*Post-RG (mm)*
NB	80	74	46	44	32	30
CD	70	70	40	38	30	32
KG	74	80	38	32	36	48
RJ	68	66	38	32	30	32
SD	74	72	34	34	40	38
VE	64	62	32	34	32	28
TM	76	78	26	22	50	56
	Average change in the total upper airway (UA) height	2.86 mm				
	Average change in RP height	3.14 mm				
	Average change in RG height	4.29 mm				

RP, Retropalatal; *RG*, retroglossal.

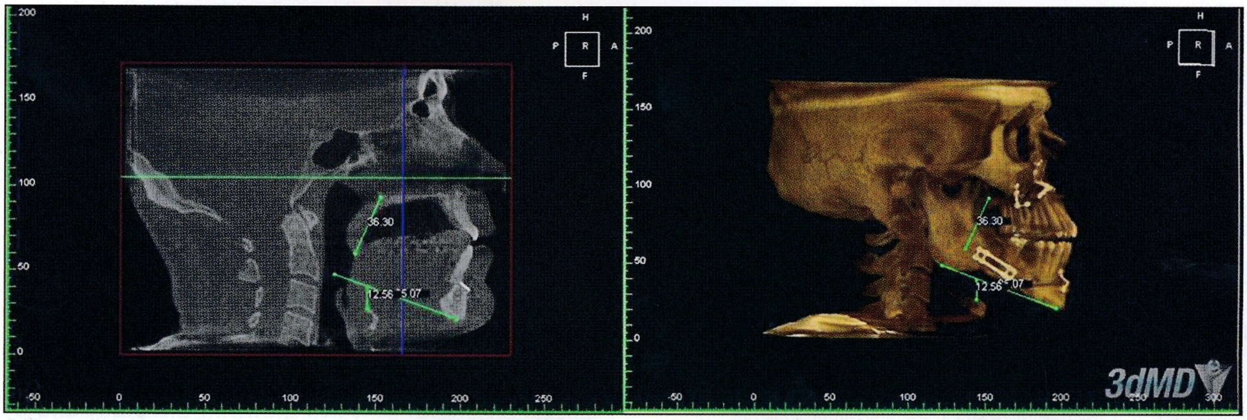

Fig 6. Hyoid bone and palate length after surgery.

Table VIII. Changes in the soft palate length and hyoid-mandibular plane measurement with surgery

Patient	*Preoperative soft palate length (mm)*	*Postoperative soft palate length (mm)*	*Preoperative hyoid-mandible (mm)*	*Postoperative hyoid-mandible (mm)*
NB	47.75	47.05	27.22	19.78
CD	42.6	41.6	17.8	12.91
KG	35.63	34.11	24.81	24.61
RJ	38.67	36.3	13.13	12.56
SD	42.69	43.65	26.62	26.17
VE	36.69	37.74	17.7	15.58
TM	29.73	28.23	21.25	22.77
RC	33.1	31.35	23.5	21.6
NS	41.7	40.6	19.6	18.5
MS	36.6	36.1	16.3	15.9

groups. They also found the usual choke point to be in the retroglossal space. It was also seen that the airway at first enlarged with growth but then after age 35 began a systematic reduction in size. The smallest airway area in this study was in a 45-year-old. The relationship between abnormal upper airway and OSA has also been established.[12] One study has shown a statistically significant relationship between the most narrow cross section of the upper airway and the probability of OSA.[1,2,13] A small airway area of about 40 to 67 mm^2 is associated with OSA. There are several reports of upper airway analysis in patients undergoing OSA surgery with MMA. Fairburn et al[17] studied 20 patients and showed significant increases in both lateral and anteroposterior airway dimensions with MMA. They concluded that the changes were secondary to the enlargement of the entire velopharynx by elevating the tissues and increasing the tension on the suprahyoid and velopharyngeal musculature. This was also confirmed by Abramson et al,[16] who concluded that decreased airway resistance after MMA was secondary to a shorter and wider airway. Based on Pouseille's law, which states that as the radius increases and height decreases, resistance decreases. Therefore, increases in surface area due to increases in the anteroposterior and transverse dimensions combined with a decrease in total airway height result in a total decrease in airway resistance. Airway resistance was most likely also decreased because of an increase in airway volume and a decrease in airway height; however, this was not specifically measured but has been shown by others to be relevant.

The length of the soft palate was essentially unchanged with surgery. Ronchi et al[23] have also shown that MMA in the treatment of OSA is effective in patients without skeletal anomalies.

Powell et al[24] evaluated 4 patients who underwent MMA for OSA by 3D computed tomography imaging and computational fluid dynamics modeling. Pharyngeal airflow below the minimum cross-sectional area showed airflow separation that generated recirculation and enhanced turbulence. After surgery, the airflow instabilities vanished. Airway resistance also improved with treatment. Similar results were found in 8 patients in another study by computational fluid dynamic analysis.[25]

Recently, bimaxillary rotation advancement has been shown to be effective in the surgical treatment of OSA.[26] The volume and morphologic changes in this study were similar to what we found with straight MMA, even though the 3D calculations were performed differently. MMA by rotation advancement might be preferable in some patients because of esthetic concerns. However, these studies are not comprehensive and did not use accurate software for upper airway analysis. All of these studies included awake patients, sometimes sitting and other times lying down during the study.

In this study, as others have shown, MMA enlarged the upper airway significantly.[18] In addition, there is a corresponding improvement in the AHI. The airway, however, not only enlarges but also changes shape, becoming more ovoid and shorter. Probably the most outstanding finding is the increase in the transverse airway dimension that is always larger than the anteroposterior increase; this is counterintuitive, since the main surgical movement is in the anterior direction. This has recently been shown by Brown et al[27] with mandibular anterior positioning devices using awake magnetic resonance imaging scans during the actual use of the mandibular device. They speculated that this is secondary to the lateral wall tissue connections to the lateral mandible. A similar action might be taking place here, although it is unknown how the change in mandibular length from surgery influences this. Knowledge of the preoperative smallest cross-sectional area (choke-point size) and position allows the surgery to be more precisely planned. For example, a small retropalatal choke point is not improved much by only a mandibular advancement, no matter how large; thus, a maxillary advancement is mandated. Conversely, a small retroglossal cross-sectional area can be entirely corrected by mandibular advancement if it is sufficiently large.

This study accounts for airway shape and size only when the patient is awake and in an upright, seated position and is static. When the patient is in the supine position and asleep, the tissues further relax and obstruct the airflow. Thus, any measurements of the airway will actually be worse during normal sleeping in the supine position when the muscles relax. Furthermore, this study was limited by a small sample size. More work needs to be done in this area to allow precise planning based on the expected airway changes with surgery.

CONCLUSIONS

The results of this study indicate that MMA for the treatment of OSA results in an increase in the oropharyngeal airway, which is associated with improvement in the postsurgical PSG. MMA as shown in this study and by others is an effective treatment option with a high degree of success for patients with OSA who cannot tolerate CPAP or wish to have a definitive correction of the condition.[22,28]

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