Research Article

Validating the Starling Resistor Model of Airway Collapse in Children and Adults

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Abstract

Background: The Starling Resistor Model was first applied to the airway in 1963 and to the pathophysiology of obstructive sleep apnea (OSA) in 1978. This applied concept of the Starling Resistor model was not popularized and described as the root cause of upper airway collapse in OSA until 1996. Starling himself first reported his "cardiac resistor model" in 1912 as he applied it to blood pressure and temperature changes in the mammalian heart. As applied to upper airway collapse, the Starling Resistor model proposes that an increase in nasal resistance will cause a subsequent reduction in pharyngeal airway volume, and a reduction in nasal resistance will increase pharyngeal volume. Thus, the volume of the flexible portion of the airway, i.e. the pharynx, is vulnerable to and dependent upon nasal patency. If true, improved nasal breathing in patients should relax the pharyngeal musculature and increase pharyngeal volume. In this study we used a minimally invasive nasal surgical model, 3-dimensional CT imaging, and NOSE scores to evaluate changes in the retro-lingual space after nasal airway surgery in adults and children after relief of nasal obstruction.

Study design and method: This is a prospective study designed to evaluate changes in the retro-lingual space in children and adults with nasal obstruction before and after minimally invasive nasal airway surgery. 15 children with nasal obstruction, and who did not have adenoid/tonsils hypertrophy, and 20 adults with nasal obstruction were included in this study. No palatal expansion or pharyngeal/tonsil surgery had been performed in any of the patients as part of this study. Pre and post-operative 3D CT-sinus images were used to calculate retro-lingual space volume, minimal cross-sectional area, hyoid bone position and lateral pharyngeal wall position. These images were obtained at 1 week pre-surgery and 3 months post-surgery. Data was analyzed and compared using paired t-test. NOSE scores were also obtained for each patient at the time of their CT imaging to determine the subjective impact of surgery.

Result: 15 pediatric patients aged 6-14 years (M 53%; F 47%) and 20 adults aged 25-76 years (M30%: F 70%) were enrolled in the study. All patients demonstrated significant increase in retro-lingual space volume and retro-lingual minimum cross-sectional area after surgery (p < 0.0001), and all patients demonstrated increase in transverse distance between pharyngeal walls after surgery (p < 0.001). Slight forward movement of Hyoid bone position in the horizontal plane was found in 34 patients (97%). Minimum cross-sectional area in both children and adults increased 81% and 98%, respectively, and retro-lingual volume increased in both children and adults 92.5% and 72.5%, respectively. Pre-op NOSE scores averaged 59 and 65, for children and adults, respectively, and post-op NOSE scores averaged 8 and 11, respectively. NOSE score changes were highly significant in both groups.

Conclusion: Adults and children with nasal obstruction and without adeno-tonsillar hypertrophy demonstrated significant increase in retro-lingual space volume and minimum cross-sectional area after minimally invasive nasal airway surgery alone to correct nasal obstruction.

INTRODUCTION

In the past 2 decades, interest in nasal obstruction in children and adults has increased significantly. In 2009, Dr. DeYun Wang used computational flow dynamics to model nasal breathing and showed that air flow actually arcs through the nose, ascending from the nostrils through the middle meatus (the primary pathway) before descending again down the nasopharynx. There is a secondary airflow pathway inferiorly along the length of the inferior turbinate. Based on this airflow model, we designed a minimally invasive surgical procedure to address the anatomic "choke points" along this arc. This procedure would theoretically reduce nasal resistance, and according to the Starling Resistor model, reduce pharyngeal airway collapse.

While Starling initially introduced his model to help explain how pressure and temperature affect cardiac function, it was subsequently studied and applied to airway ventilation (by Permut; Remmer), and obstructive sleep apnea (by Gold and Schwartz). The concept states that upstream resistance to flow will cause a subsequent reduction in the cross-sectional area of a distensible tube distal to the obstruction. Conversely, reducing upstream resistance will reduce this downstream collapse. To our knowledge, this principle, while intuitive, has never been

formally tested in humans with an obstructed nasal airway.

Thus, nasal obstruction, especially during sleep, may be an important issue for patients with sleeps disordered breathing. If the Starling Resistor model is correct, then reducing nasal resistance should reduce pharyngeal collapse and reduce airway obstruction. This concept could have a profound impact on the treatment of patients with sleep disordered breathing, including obstructive sleep apnea.

Our surgical approach to the treatment of nasal airway obstruction targets the main anatomic structures that impact nasal airflow along the intranasal airway arc [1,2] as described by Dr. Wang. These include the entire septum, nasal valves, septal swell body, middle meatus, middle and inferior turbinates, and the nasopharynx. In this study, we evaluate the changes in retro-lingual space using 3-dimensional CT measurements following our minimally invasive nasal procedures alone in children and adults for the relief of nasal obstruction. No patient had pharyngeal or nasopharyngeal surgery during the study, nor enlarged tonsils or adenoids.

MATERIALS AND METHODS

This is a prospective study of 15 pediatric and 20 adult patients who had nasal obstruction without adeno-tonsillar hypertrophy who underwent minimally invasive nasal airway surgery. Any patient with adenoid hypertrophy, tonsil hypertrophy, or has used any form of palate expander was excluded from the study.

Table 1P: Pediatric Patient Demographics.	
Patient #	15
Average age(years)	10.1
Minimum age(years)	6
Maximum age(years)	14
Male%	53
Female%	47
Expander	0
Adenoid/tonsils hypertrophy	0

Table 1A: Adult Patient Demographics.	
Patient #	20
Average age(years)	52
Minimum age(years)	25
Maximum age(years)	76
Male%	30
Female%	70
UPPP	0
Adenoid/tonsils hypertrophy	0

Fifteen pediatric and 20 adult patients diagnosed with nasal obstruction were included in this study and evaluated in the outpatient otolaryngology clinic. All of the patients also met the diagnosis of chronic sinusitis (CRS) or recurrent acute rhinosinusitis (RARS) and were deemed refractory to medical management by their comprehensive history. History, physical exam, NOSE scores, and 3-D sinus CT-scan using the iCAT Cone Beam CT (CBCT) were obtained. Patients were seated during imaging with their head strapped to the head holder. The CBCT scan sequence takes only 7 seconds to complete, therefore patients were asked to breath quietly and regularly through their nose with their mouths closed once the scan was initiated. Patients were not allowed to swallow while the images were being obtained. This established flow through the upper airway as required by the Starling model.

The most common nasal obstructive symptoms included mouth breathing, snoring, orthodontic care, and difficulty with nasal breathing during exercise. The CT images and endoscopic nasal exam confirmed the diagnosis clinically, and patient history and chief complaint were highly supportive of the diagnosis. All patients underwent minimally invasive nasal airway surgery to include some combination of the following: endoscopic septoplasty, bilateral radiofrequency ablation of the septal swell body and inferior turbinates, bilateral uncinectomy, anterior ethmoidectomy, and unilateral or bilateral concha bullosa resection if present (Table 2P, 2A).

Table 2P: Procedures performed for each patient (pediatric group).			
	Surgery done		**Septal swell body RFA**
1	Uncinectomy/a. ethmoidectomy/ septoplasty/ turbinates reduction		Y
2	Uncinectomy/ a. ethmoidectomy/ septoplasty/ turbinates reduction		N
3	Uncinectomy/ a. ethmoidectomy/ turbinates reduction		Y

4	Uncinectomy/a. ethmoidectomy/ turbinates reduction	Y
5	Uncinectomy/ a. ethmoidectomy/ septoplasty/turbinates reduction/concha resection	Y
6	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
7	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
8	Uncinectomy/ a. ethmoidectomy/septoplasty/turbinates reduction	Y
9	Uncinectomy/septoplasty/turbinates reduction/concha resection	N
10	Uncinectomy/a. ethmoidectomy/turbinates reduction	Y
11	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction/concha resection	N
12	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
13	Uncinectomy/ a. ethmoidectomy/septoplasty/turbinates reduction	Y
14	Uncinectomy/ a. ethmoidectomy/turbinates reduction/concha resection	Y
15	Uncinectomy/ a. ethmoidectomy/turbinates reduction	Y

Table 2A: Procedures performed for each patient (adult group).

	Surgery done	Septal swell body RFA
1	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
2	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
3	Uncinectomy/ a. ethmoidectomy/septoplasty/turbinates reduction	Y
4	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
5	Uncinectomy/ a. ethmoidectomy/septoplasty/turbinates reduction	Y
6	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
7	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	N
8	Uncinectomy/ a. ethmoidectomy/septoplasty/turbinates reduction	Y
9	Uncinectomy/ a. ethmoidectomy/septoplasty/turbinates reduction	N
10	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
11	Uncinectomy/ a. ethmoidectomy/septoplasty/turbinates reduction	Y
12	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
13	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
14	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
15	Uncinectomy/ a. ethmoidectomy/turbinates reduction	Y
16	Uncinectomy/ a. ethmoidectomy/septoplasty/turbinates reduction	Y
17	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
18	Uncinectomy/a. ethmoidectomy/septoplasty/turbinates reduction	Y
19	Uncinectomy/ a. ethmoidectomy/septoplasty/turbinates reduction	Y
20	Uncinectomy/a. Ethmoidectomy/septoplasty/turbinates reduction	N

Follow-up visits were 3-weeks, and 3 months post-operatively.

A 3-D sinus CT-scan was again obtained using the same machine and the same head and neck positioning 3 months post-operatively, and processed using the same imaging software for comparison. Nasal breathing with a closed mouth began once the scan sequence was initiated. NOSE scores were also obtained at their 3 month post-op visit and compared to baseline scores.

Pre-op and post-op 3-D CT images for each patient were processed and measurements of retro-lingual space volume, minimum cross-sectional area, transverse distance between pharyngeal walls, and hyoid bone position were performed by the following protocol:

3-D CT images were processed using i-CAT Vision software and Ⓧvolume and minimum cross-sectional area of retro-lingual space determined from the level of hard palate to the level of inferior aspect of hyoid bone (Figures 1 and 2).

2-D CT axial images were also analyzed to measure the transverse distance between pharyngeal walls at the level of inferior border of C2 (Figures 3 and 4).

To determine the hyoid bone position and detect the direction of its positional change after surgery, we used 2D CT midline sagittal images, and used a horizontal line parallel to hard palate plane and passing through the superior anterior edge of C3, and another line vertical to hard palate plane and passing through the superior anterior edge of hyoid bone. From the intersection of these lines, we

measured the horizontal distance to the superior anterior edge of C3 and the vertical distance to the superior anterior edge of hyoid bone (Figures 5 and 6).
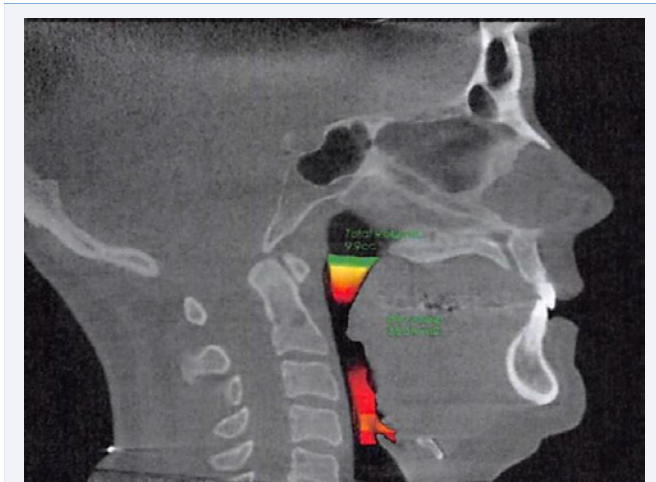
Figure 1 Pre-op retro-lingual space volume and minimum cross-sectional area (Adult).
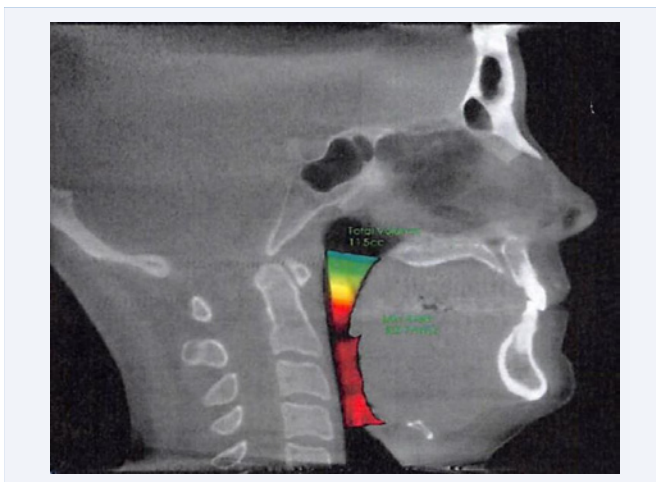
Figure 2 Post-op retro-lingual space volume and minimum cross-sectional area.
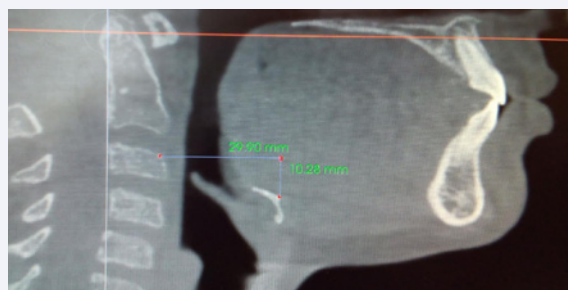

Figure 3 Pre-op transverse distance between pharyngeal walls measurement(Child).

Figure 4 Post-op transverse distance between pharyngeal walls measurement.

Figure 5 Pre-op Hyoid bone position measurement(Child).

Figure 6 Post-op Hyoid bone position measurement.

RESULTS

NOSE Scores

Baseline NOSE scores averaged 59 and 65, for children and adults, respectively, and post-op NOSE scores averaged 8 and 11, respectively. NOSE score changes were highly significant in both groups.

Retro-lingual Volume

35 pre-op and 35 post-op 3-D CT scans were analyzed as described. The average pre-op retro-lingual space volume in *children* was 5.4 cm^3 (STDEV 3.11), and average post-op retro-lingual space volume was 10.40 cm^3 (STDEV 4.05) (Figure 7P). Thus, the average increase in volume post operatively was 5 cm^3 (Figure 8P), and the average percentage increase in retro-lingual volume post-operatively in *children* was 92.5%. The average pre-op retro-lingual space volume in *adults* was 10.9 cm^3(STDEV 4.25), and the average post-op retro-lingual space volume was 17.6 cm^3 (STDEV 6.88) (Figure 7A). Thus, the average increase in volume post-operatively was 6.7 cm^3 (Figure 8A), and the average percentage increase in retro-lingual volume post-operatively in *adults* was 72.5%.
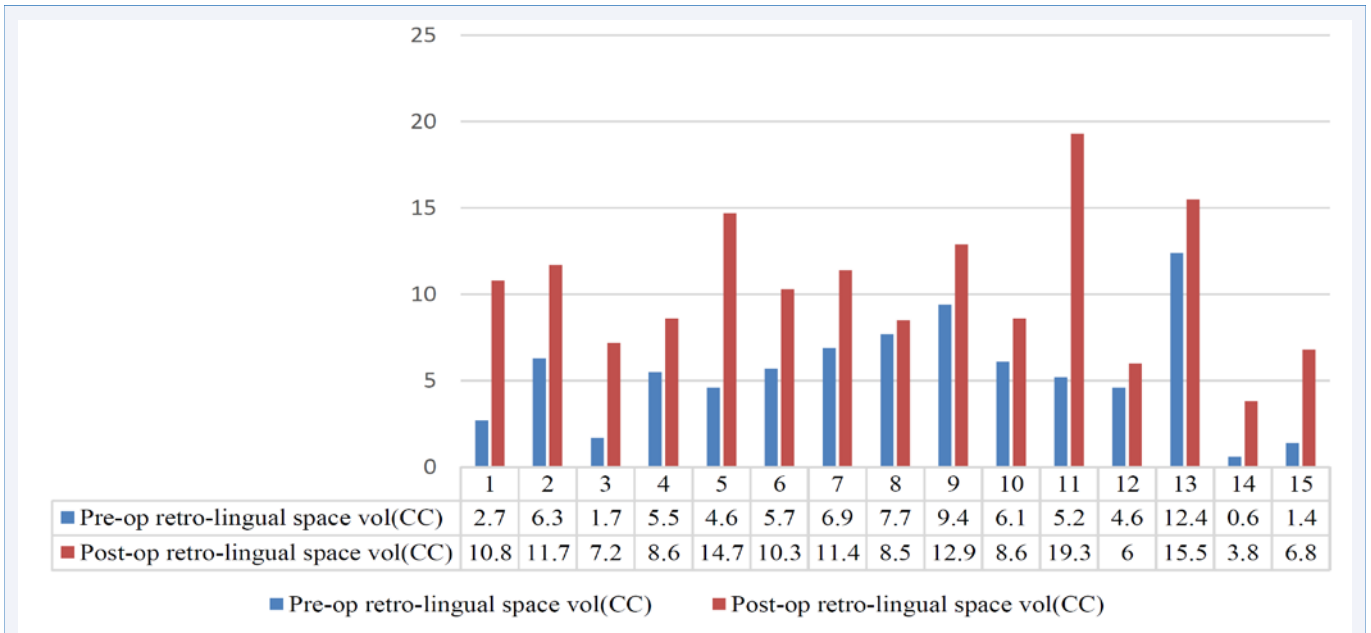
Figure 7p Pre-op and post-op retro-lingual space volumes in pediatric group.

Pre-op retro-lingual space vol(CC)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
■ Pre-op retro-lingual space vol(CC)	2.7	6.3	1.7	5.5	4.6	5.7	6.9	7.7	9.4	6.1	5.2	4.6	12.4	0.6	1.4
■ Post-op retro-lingual space vol(CC)	10.8	11.7	7.2	8.6	14.7	10.3	11.4	8.5	12.9	8.6	19.3	6	15.5	3.8	6.8
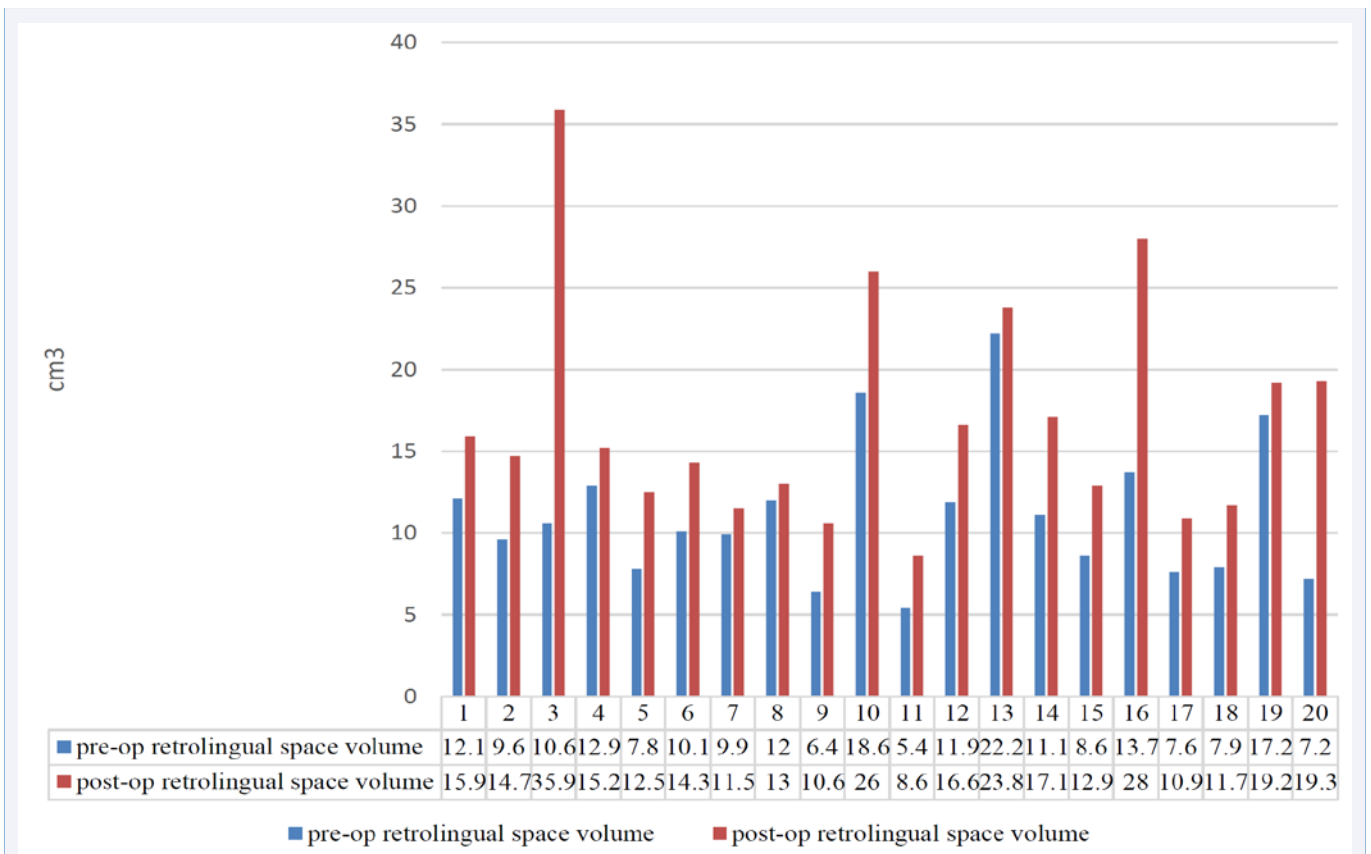
Figure 7a Pre-op and post-op retro-lingual space volumes in adult group.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
■ pre-op retrolingual space volume	12.1	9.6	10.6	12.9	7.8	10.1	9.9	12	6.4	18.6	5.4	11.9	22.2	11.1	8.6	13.7	7.6	7.9	17.2	7.2
■ post-op retrolingual space volume	15.9	14.7	35.9	15.2	12.5	14.3	11.5	13	10.6	26	8.6	16.6	23.8	17.1	12.9	28	10.9	11.7	19.2	19.3

Paired t-test in each group showed a significant difference between pre-op and post-op retro-lingual volumes (P < 0.0001).

Minimum Cross-sectional Area

In *children*, the average pre-op retro-lingual minimum cross-sectional area was 90.42 mm^2 (STDEV 56.622), and average post-

op retro-lingual minimum cross-sectional area was 163.73 mm^2 (STDEV 62.268) (Figure.9P). Average difference in minimum cross-sectional area post operatively was 73.3 mm^2 (Figure.10P), thus the average percentage increase in retro-lingual minimum cross-sectional area post-operatively in *children* was 81%.

Figure 8p Post-op Retro-lingual volume differences in pediatric group (mm^3).

Figure 8a Post-op Retro-lingual volume differences in adult group (mm^3).
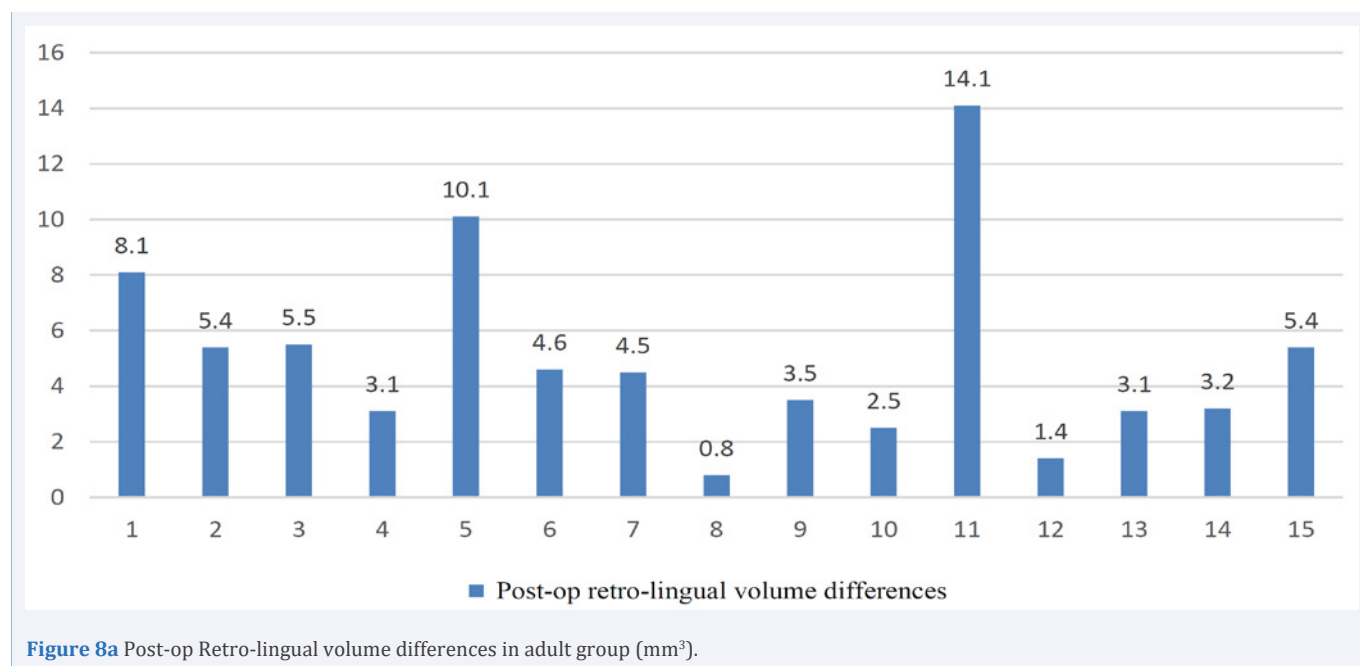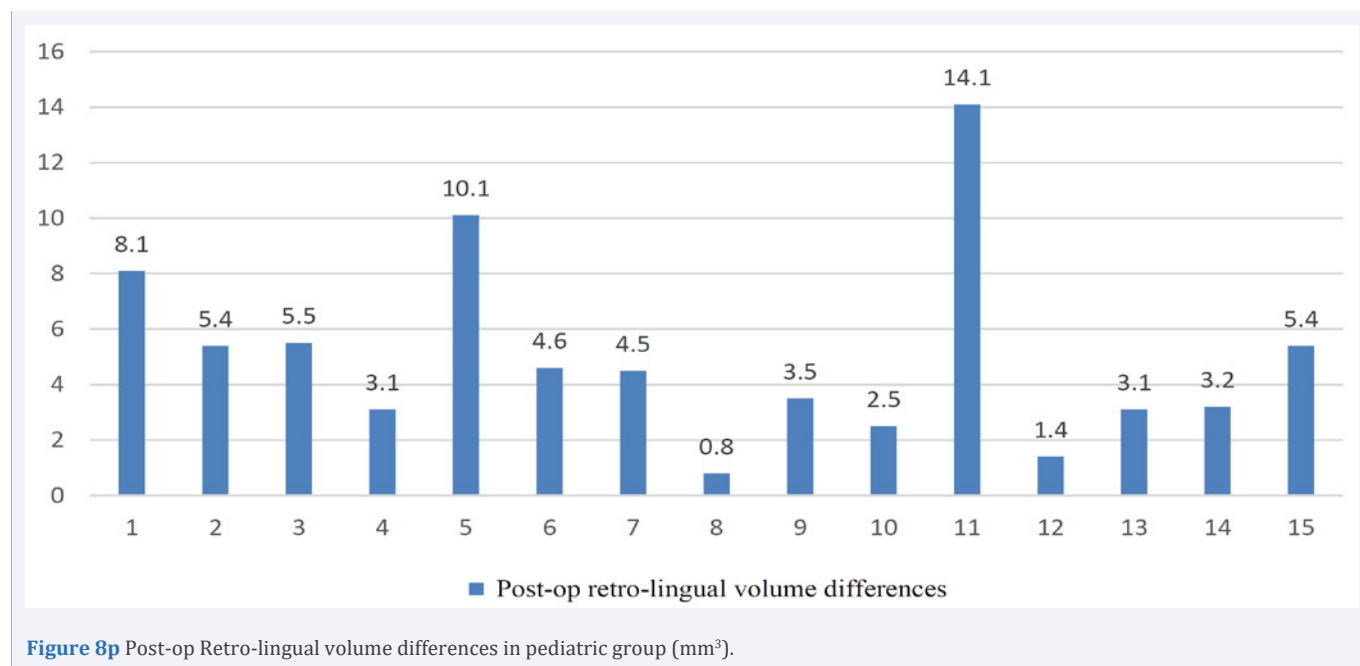
In adults, the average pre-op retro-lingual minimum cross-sectional area was 63.2 mm^2 (STDEV 39.50), and average post-op retro-lingual minimum cross-sectional area was 125.3 mm^2 (STDEV 78.08) (Figure.9A). Average difference in minimum cross-sectional area post operatively was 62.1 mm^2 (Figure.10A), thus the average percentage increase in retro-lingual minimum cross-sectional area post-operatively in *adults* was 98%.

Paired t-test was utilized and showed a significant difference between pre-op and post-op retro-lingual minimum cross-sectional area in both groups (P < 0.0001).

Transverse Distance Between Pharyngeal Walls

Average pre-op transverse distance between pharyngeal walls in *children* measured as described above was 17.03 mm (STDEV 4.552), and average post-op transverse distance between pharyngeal walls was 22.56 mm (STDEV 4.452) (Figure.11P)., thus the

average difference in transverse distance post operatively was 5.53 mm, representing an average increase of 32%. Average pre-op transverse distance between pharyngeal walls in *adults* measured as described above was 28.41 mm (STDEV 5.44), and average post-op transverse distance between pharyngeal walls was 32.43 mm (STDEV 5.74) (Figure 11A), thus the average difference in transverse distance post operatively was 4 mm, representing an average increase of 14%.

Paired t-test again showed a significant difference between pre-op and post-op transverse distance between pharyngeal walls (P < 0.0001).
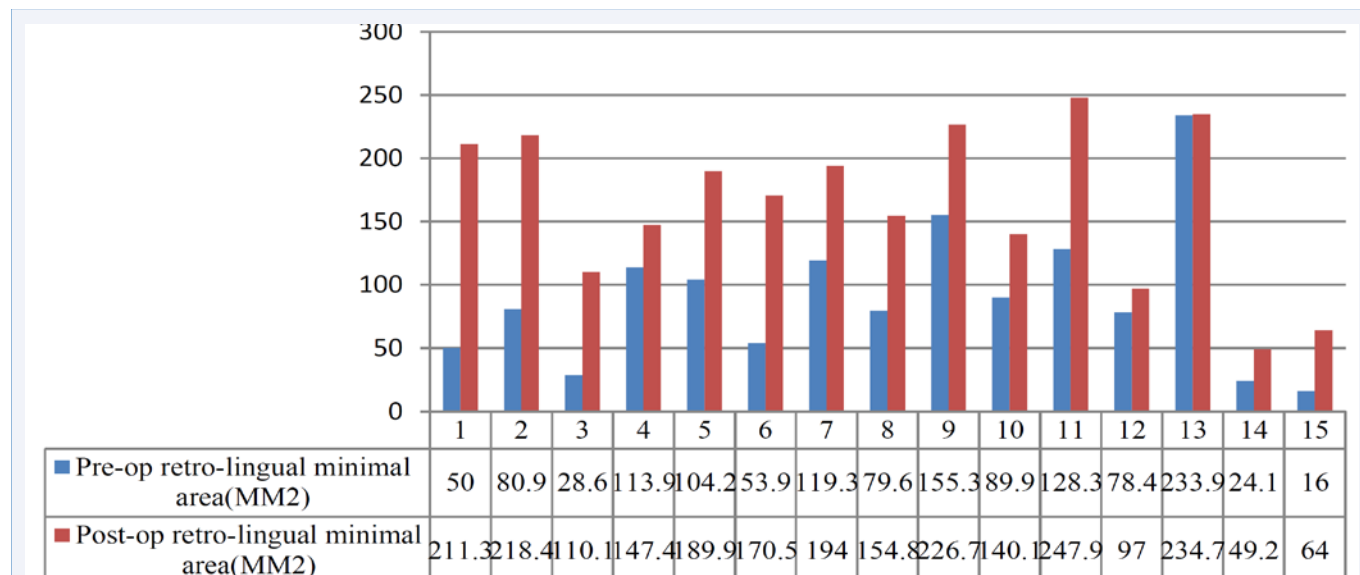

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
■ Pre-op retro-lingual minimal area(MM2)	50	80.9	28.6	113.9	104.2	53.9	119.3	79.6	155.3	89.9	128.3	78.4	233.9	24.1	16
■ Post-op retro-lingual minimal area(MM2)	211.3	218.4	110.1	147.4	189.9	170.5	194	154.8	226.7	140.1	247.9	97	234.7	49.2	64

Figure 9p Pre and post-op retro-lingual minimal area in pediatric group.

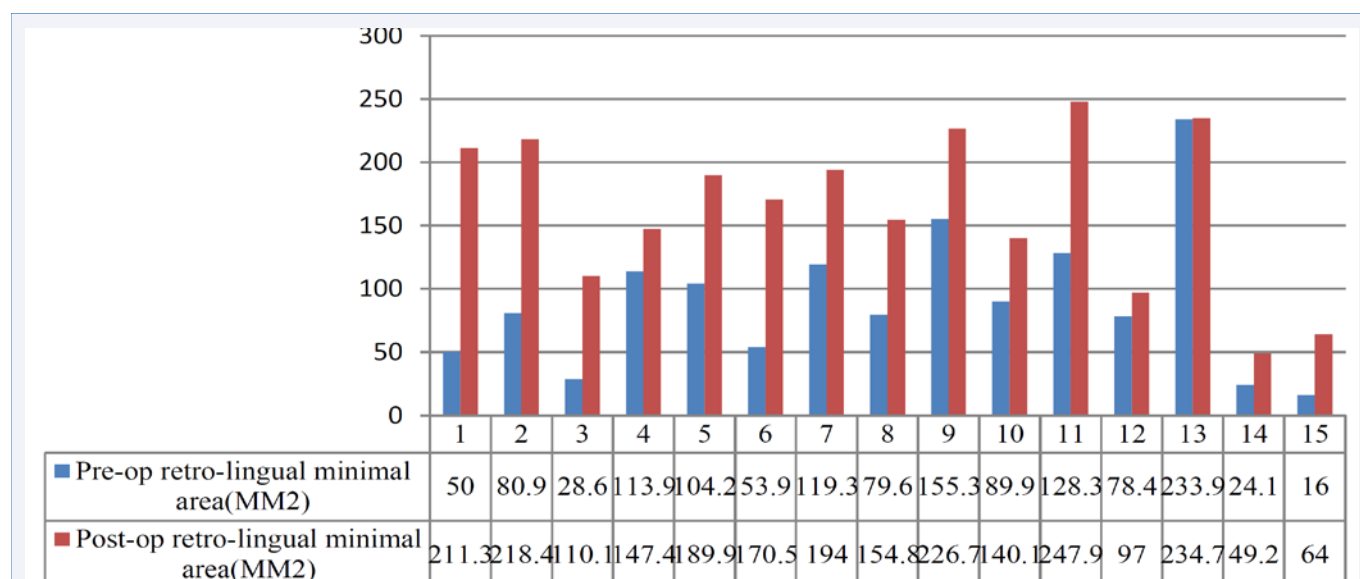|	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
■ Pre-op retro-lingual minimal area(MM2)	50	80.9	28.6	113.9	104.2	53.9	119.3	79.6	155.3	89.9	128.3	78.4	233.9	24.1	16
■ Post-op retro-lingual minimal area(MM2)	211.3	218.4	110.1	147.4	189.9	170.5	194	154.8	226.7	140.1	247.9	97	234.7	49.2	64

Figure 9a Pre and post-op retro-lingual minimal area in adult group.

Hyoid Bone Position

Hyoid bone position change in the horizontal plane was consistently slightly forward in all patients. In *children*, the average pre-op hyoid bone horizontal distance from C3 was 28.44 mm (STDEV 2.784), and average post-op horizontal distance from C3 was 30.78 mm (STDEV 2.784) (Figure.12P). Average difference in horizontal distance from C3 post operatively was 2.34 mm, representing an average change of 8%. In *adults*, the average pre-op hyoid bone horizontal distance from C3 was 36.45 mm (STDEV 4.18), and average post-op horizontal distance from C3 was 38.95 mm (STDEV 3.82) (Figure.12A). Average difference in horizontal distance from C3 post operatively was 2.5 mm, representing an average change of 7%. Paired t-test showed both of these changes to be significant (P= 0.0001).

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Hyoid bone position in the vertical plane was inconsistent with respect to the direction of change with a downward directional change found in 11 pediatric and 4 adult patients, an upward directional change in 4 pediatric and 14 adult patients, and no change in 2 adults.
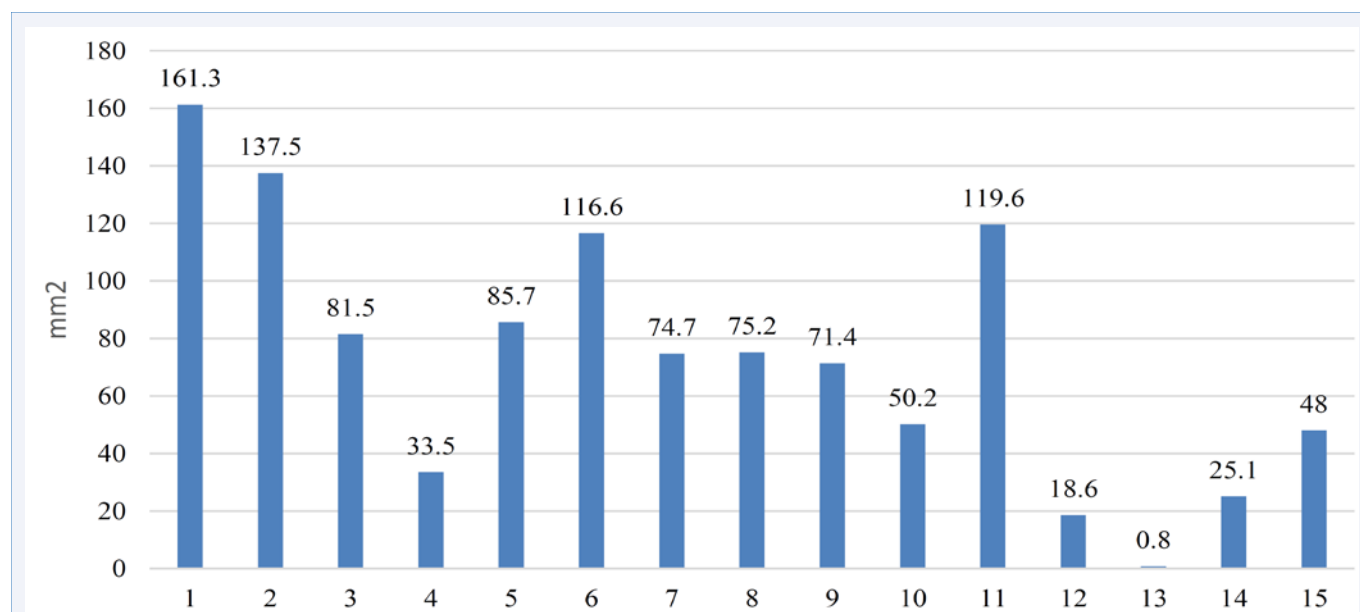

Figure 10p Pre and post-op retro-lingual minimal area differences in pediatric group.
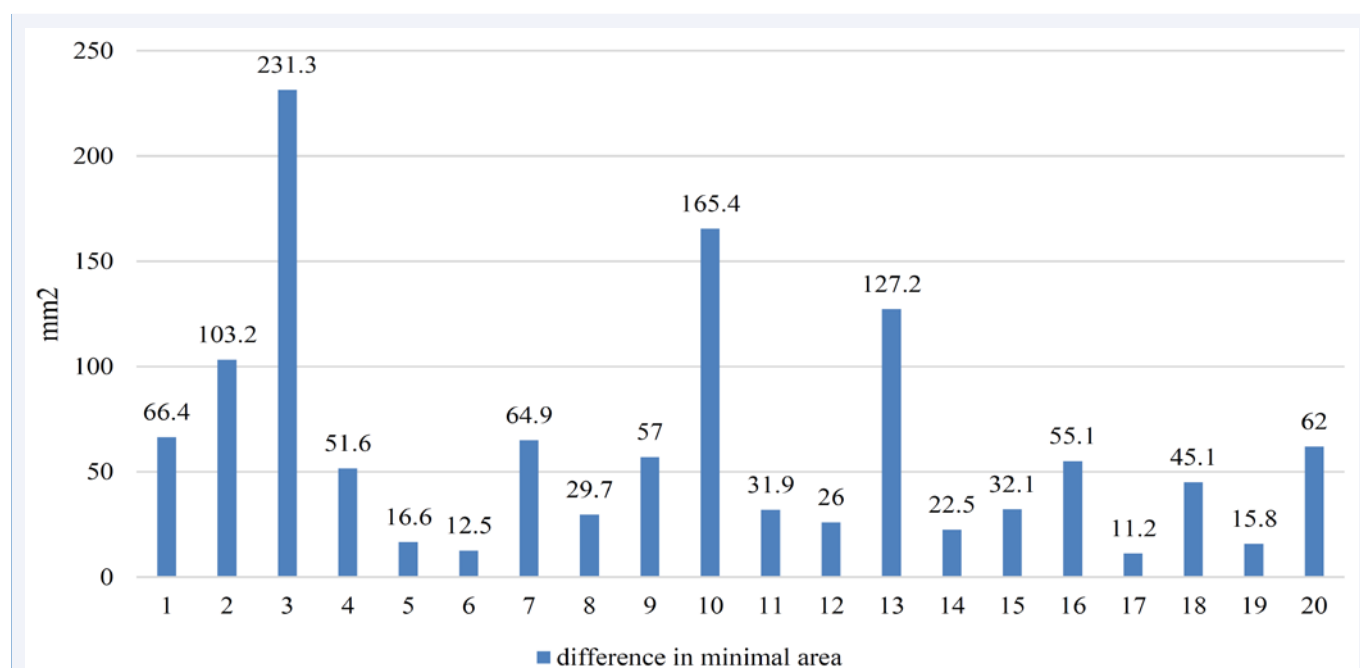

Figure 10a Pre and post-op retro-lingual minimal area differences in adult group.

DISCUSSION

Interestingly, many patients who suffer from nasal obstruction are unaware of their condition. This is especially true in children. The two main reasons for this are (a) positional congestion and (b) subjective variability. The former (a) occurs only while supine during sleep. It takes about 30 to 90 minutes for nasal congestion to develop when supine, and by then the patient is often already asleep, and thus, unaware of the problem. This positional congestion primarily develops in the middle and inferior turbinates, and septal swell body. The latter reason (b), or variability in subjective or self-awareness of nasal congestion, is due to the fact that many of these patients have had chronic nasal obstruction since early childhood and have no frame of reference for normal nasal breathing. It

is for this same reason that children undergo mandatory hearing and vision testing early in grade school; their subjective appreciation of "normal" is unreliable.
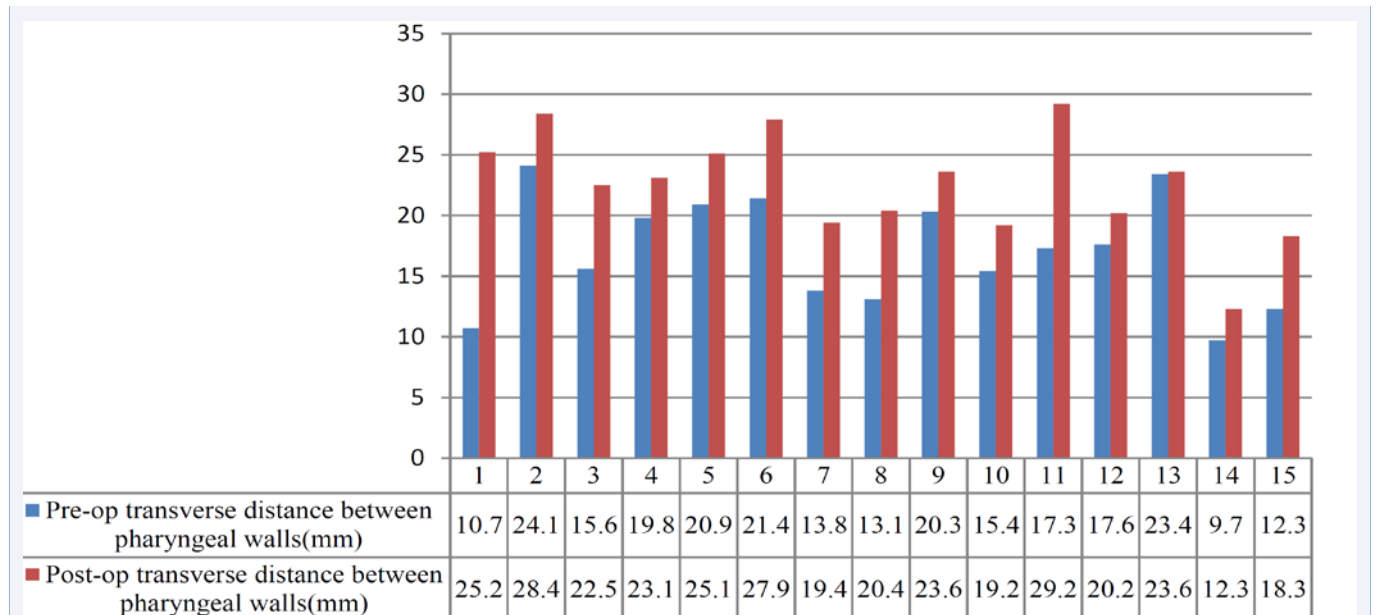

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
■ Pre-op transverse distance between pharyngeal walls(mm)	10.7	24.1	15.6	19.8	20.9	21.4	13.8	13.1	20.3	15.4	17.3	17.6	23.4	9.7	12.3
■ Post-op transverse distance between pharyngeal walls(mm)	25.2	28.4	22.5	23.1	25.1	27.9	19.4	20.4	23.6	19.2	29.2	20.2	23.6	12.3	18.3

Figure 11p Pre and post-op transverse distance between pharyngeal walls (mm) in pediatric group.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
■ pre-op transverse distance between pharyngeal walls (mm)	29.3	19.7	31.7	35.5	32	26.7	23.4	31	22.6	39.6	26.2	28.5	31.6	24.7	33.4	33.2	25.2	20.4	33.7	22.2
■ post-op transverse distance between pharyngeal walls (mm)	33	24.2	32.4	36.3	32.4	34.3	23.4	32.5	30.4	40.3	28.3	29	32.1	35.2	35.5	35.7	33.7	21.3	35	35.3

■ pre-op transverse distance between pharyngeal walls (mm)   ■ post-op transverse distance between pharyngeal walls (mm)
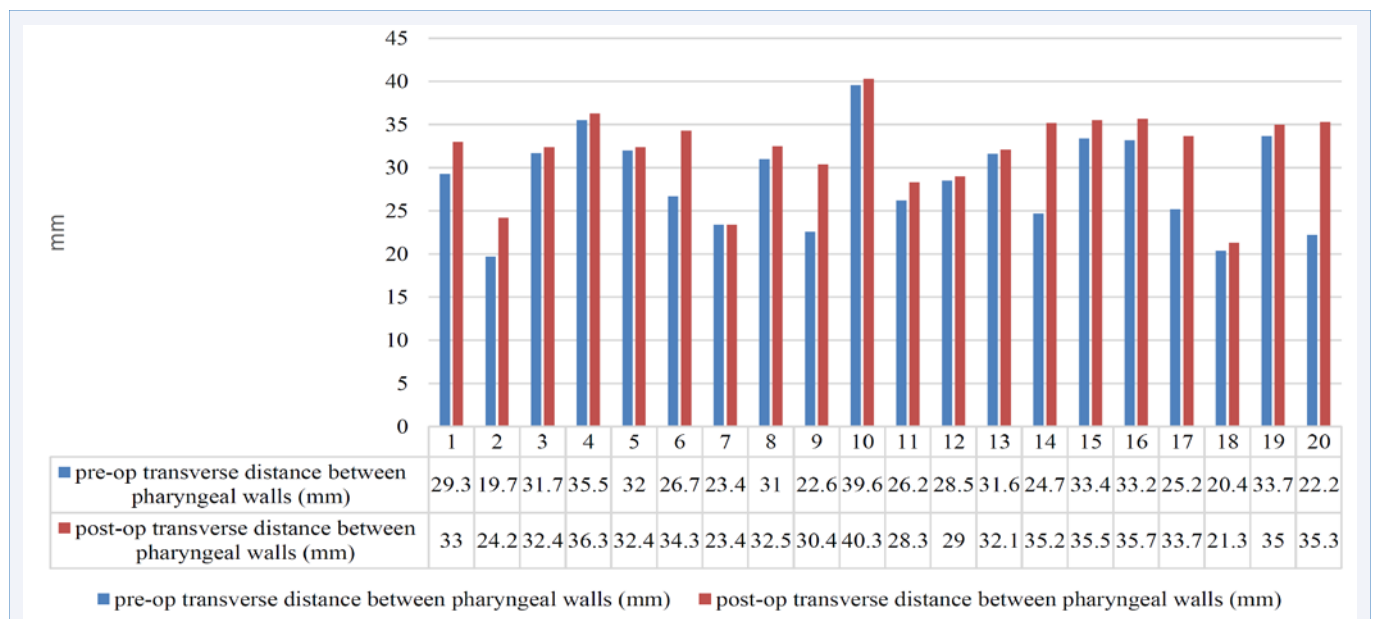
Figure 11a Pre and post-op transverse distance between pharyngeal walls (mm) in adult group.

The importance of nasal breathing on craniofacial growth and development was proven in a landmark experiment by Harvold in baby rhesus monkeys[3] in the late 1970's. In that study, Harvold took two groups of baby monkeys, and in one of the groups silicone plugs were sutured into their nostrils. After 6 months, the effect of mouth breathing was obvious on craniofacial development in that group compared to the monkeys without nasal obstruction - the nasally obstructed monkeys developed classic adenoid facies with high arched palates and narrow maxillas. Another variable measured in that experiment is the tonicity of facial and upper airway musculature. EMG of facial and upper airway musculature in the obstructed nasal airway group showed abrupt rhythmic discharge patterns, which was different from the continuous low amplitude and desynchronized discharges patterns that are seen in the normal subject's group. After 6-months, the nasally obstructed monkeys had the plugs removed and were allowed to breathe through their nose again, and normal EMG patterns were restored and some of the cranio-facial abnormalities began to normalize. The most important conclusions from this experiment are that nasal breathing is of great importance because it is directly responsible

for adequate craniofacial growth in the young, and that restored nasal breathing in young patients may allow reversibility of early cranio-facial growth restriction. Cranio-facial restriction is directly related to the development of crooked teeth, a high arched palate, and narrow maxilla. Thus, the need for orthodontic care has a direct correlation to impaired nasal breathing, as seen in many of our study patients.
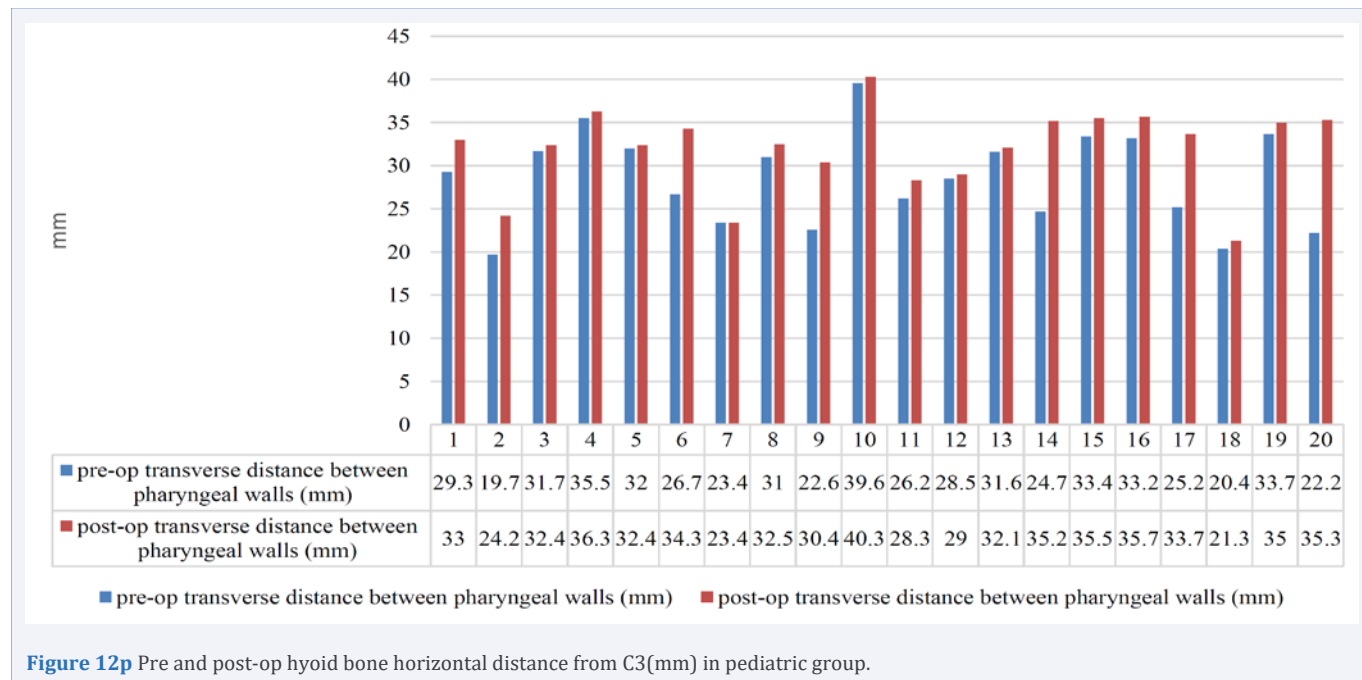

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
pre-op transverse distance between pharyngeal walls (mm)	29.3	19.7	31.7	35.5	32	26.7	23.4	31	22.6	39.6	26.2	28.5	31.6	24.7	33.4	33.2	25.2	20.4	33.7	22.2
post-op transverse distance between pharyngeal walls (mm)	33	24.2	32.4	36.3	32.4	34.3	23.4	32.5	30.4	40.3	28.3	29	32.1	35.2	35.5	35.7	33.7	21.3	35	35.3

■ pre-op transverse distance between pharyngeal walls (mm)   ■ post-op transverse distance between pharyngeal walls (mm)

Figure 12p Pre and post-op hyoid bone horizontal distance from C3(mm) in pediatric group.

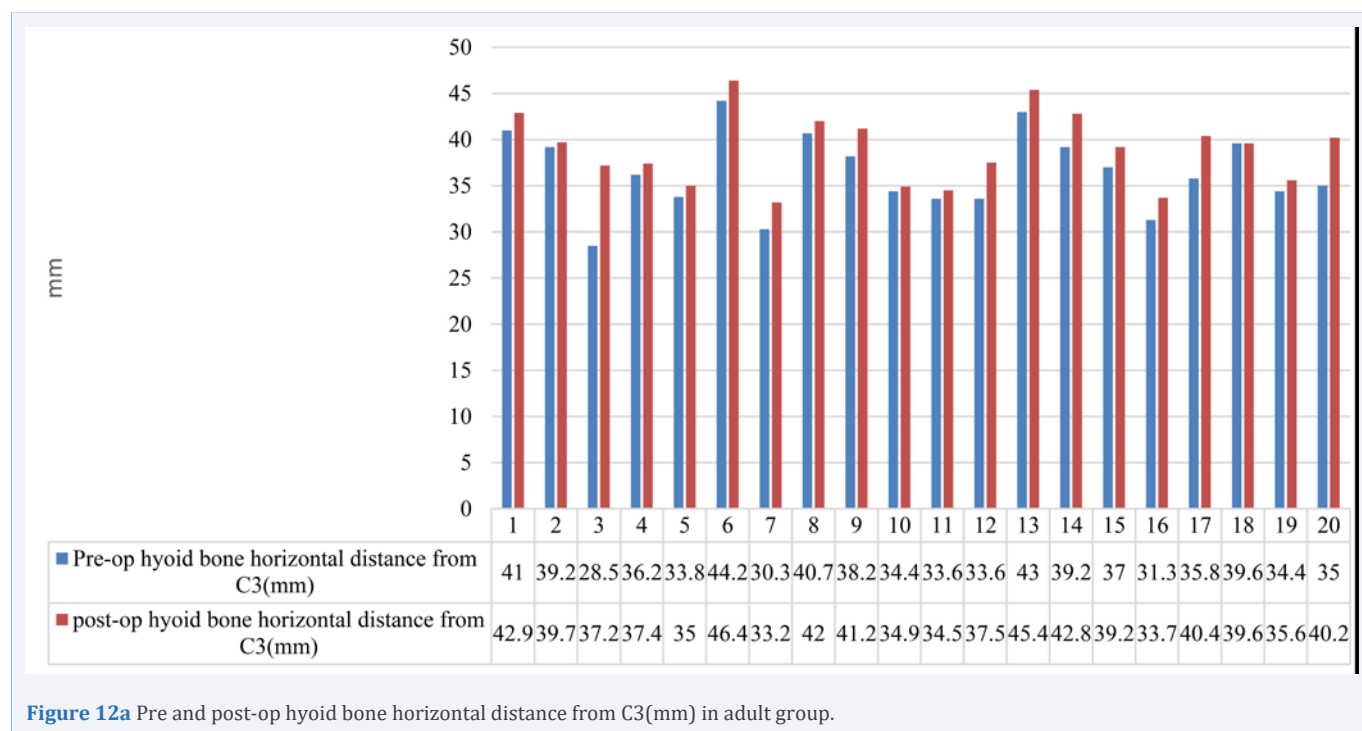|	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Pre-op hyoid bone horizontal distance from C3(mm)	41	39.2	28.5	36.2	33.8	44.2	30.3	40.7	38.2	34.4	33.6	33.6	43	39.2	37	31.3	35.8	39.6	34.4	35
post-op hyoid bone horizontal distance from C3(mm)	42.9	39.7	37.2	37.4	35	46.4	33.2	42	41.2	34.9	34.5	37.5	45.4	42.8	39.2	33.7	40.4	39.6	35.6	40.2

Figure 12a Pre and post-op hyoid bone horizontal distance from C3(mm) in adult group.

The traditional surgical approaches used to treat nasal obstruction, namely septoplasty and inferior turbinoplasty, were lacking contemporary knowledge of nasal airflow dynamics and the most important anatomic areas in the nasal cavity that increase nasal resistance. Recently, via computational fluid dynamics (CFD) applied to the nasal cavity, we learned more about the anatomical structures in the nasal cavity that play an important role in nasal patency and airflow[1,2]. We have modeled our surgical intervention

in these study patients to address the anatomic areas that most impact nasal resistance. The removal of the uncinate process and anterior ethmoid bulla was performed in all patients based on the work by Dr Xiong et al[4] in 2011, who showed that removal of these structure increases nasal airflow by 15%.

There is also a concern by many otolaryngologists about performing septoplasty in children under age 16, however several longitudinal studies shown that nasal and sinus surgery in children, including septoplasty, is completely safe as long as the septal mucoperichondrium is preserved [5]. We also now know that NOT correcting nasal obstruction in children with SDB will adversely influence craniofacial growth, dental and jaw position [6,7], etc. Therefore, the current thinking is that the risk of properly performed minimally invasive nasal surgery, including septoplasty, in children, is far less than the risk of untreated nasal obstruction.

The 3D CT image in our study were taken with the patient's head strapped to the head holder in the same exact position each time, and with a slow steady nasal breath as the scan was initiated. This was done to best simulate flow as required by the Starling model. While there is no way to make sure each person was breathing in exactly the same manner, the overall data suggests this was quite likely as every person in the study showed improvement in NOSE scores, minimal cross-sectional area, and retro-lingual volume. The scans were also taken approximately 3 months apart to minimize any affect from the child's normal growth on these measurements. The similar improvements seen in adults supports the findings seen in children as not related to "growth" between scans. Of note, every patient studied showed a highly statistically significant increase in both retro-lingual pharyngeal volume and minimal cross-sectional area, demonstrating the significance of nasal breathing on pharyngeal airway dimensions. Adults showed a greater increase in minimal cross-sectional area (98%) versus children (81%), whereas children showed a greater increase in retro-lingual volume (92.5%), versus adults (72.5%).

Hyoid bone position in patients with sleep disordered breathing has been a controversial concept and many studies have tried to find a relationship or association between the two. Some studies revealed a posterior-inferior displacement of the hyoid bone in such patients, but when this displacement was adjusted to total tongue volume, it became insignificant [8]. Other studies did not find any difference at all in hyoid bone position between those with sleep disordered breathing and normal subjects [9]. In our study, both adults and children showed similar anterior movement of the hyoid bone of approximately 2.5mm, and transverse pharyngeal wall relaxation of 5.5 mm in children and 4 mm in adults. These changes represent a statistically significant forward movement of the hyoid bone after surgery, which may be attributed to muscle tone changes and normalization of hyoid position. However, there was inconsistent change in the vertical plane position that may highlight the complex interaction between the musculature attachments of the hyoid bone in each individual patient.

One may question how only a few millimeters change in any one dimension can be so influential in changing the pharyngeal volume. This is explained by the Hagen-Poiseuille Law (Flow = $Pr^4/8vL$), where P = pressure, r = radius of the tube, v = viscosity, and L = length. In this study, the only variable we have directly changed was "r", or the size of the nasal air space. Thus, increasing the nasal air space by a mere 1 mm, from 1.5 to 2.5 mm, will increase nasal air flow 8 fold!

This concept of small changes in nasal anatomy causing significant increases in nasal airflow was further supported by the significant change in NOSE scores seen in both the child and adult groups. This study was not intended to quantify the degree of nasal obstruction in patients before or after nasal airway surgery. The NOSE score has been used as a subjective measure of airflow for this purpose. While computational flow dynamics (CFD) would perhaps be the ideal way to assess flow changes, the findings reported herein are significant in that they support the Starling-Resistor Model as an accurate model of airflow through the nose and upper airway in adults and children. CFD is a time consuming process usually requiring engineering collaboration which we did not have access to.

CONCLUSION

Retro-lingual space volume and minimum pharyngeal cross-sectional area were both highly statistically significantly increased after targeted minimally invasive nasal airway surgery in adults and children relieved of their nasal obstruction, and without the need for any pharyngeal or nasopharyngeal surgery. Increase in the transverse distance between pharyngeal walls, and anterior movement of hyoid bone were also statistically significant. To our knowledge, this is the first study to support the Starling-Resistor Model as applied to the oropharyngeal airway, and may have significant implications on the treatment paradigm for patients with impaired nasal breathing and sleep disordered breathing.

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REFERENCES

1. De Yun Wang, Heow Peuh Lee, Bruce R. Gordon. Impacts of Fluid Dynamics Simulation in Study of Nasal Airflow Physiology and Pathophysiology in Realistic Human Three-Dimensional Nose Models. Clin Exp Otorhinolaryngol. 2012; 5: 181-187.

2. Kai Zhao, Jianbo Jiang. What is normal nasal airflow? A computational study of 22 healthy adults. Int Forum Allergy Rhinol. 2014; 4: 435-46.

3. EP Harvold, BS Tomer, K Vargervik, G Chierici. Primate Experiments on Oral Respiration. Am J Orthod. 1981; 79: 359-72.

4. Xiong GX, Zhan JM, Zuo KJ, Rong W, Li JE, Xu G. Use fo Computational Fluid Dynamics to Study the Influence of the Uncinate Process on nasal Airflow. J Laryngol Otol. 2011; 125: 30-7.

5. Lawrence R. Pediatric septoplasy: A review of the literature. Int J Pediatr Otorhinolaryngol. 2012; 76: 1078-81.

6. Luca D'Ascanio, Carla Lancione, Giorgio Pompa, Elena Rebuffini, Nicola Mansi, Marco Manzini. Craniofacial growth in children with

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nasal septum deviation: a cephalometric comparative study. Int J Pediatr Otorhinolaryngol. 2010; 74: 1180-1183

7. Ilknur Haberal Can, Kürş ad Ceylan, Unal Bayiz, Ali Olmez, Erdal Samim. Acoustic rhinometry in the objective evaluation of childhood septoplasties. Int J Pediatr Otorhinolaryngol. 2005; 69: 445–448.

8. Chi L, Comyn F-L, Mitra N, MP Reilly, F Wan, G Maislin, et al. Identification of Craniofacial Risk Factors for Obstructive Sleep Apnea Using Three-Dimensional MRI. Eur Respir J. 2011; 38: 348-358.

9. Bibby RE. The hyoid bone position in mouth breathers and tongue-thrusters. Am J Orthod. 1984; 85: 431-433.

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