

ORIGINAL RESEARCH

Hyoid expansion with titanium plate and screws with hyomandibular suspension: A study on human cadavers with computed tomographic comparative analysis

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Abstract

Objective(s): Obstructive sleep apnoea is characterized by repetitive obstruction of the upper airway during sleep. These repeated oxygen desaturations increase cardiovascular and cerebrovascular morbidity and mortality significantly. Upper airway surgery is an option for patients who fail continuous positive airway pressure therapy. Airway collapse is usually multilevel and hypopharyngeal collapse is a challenging area to address. It is hypothesized that hyoid expansion with hyomandibular suspension can potentially increase upper airway dimensions at the hypopharynx. This study aims to document the effect of hyoid expansion using titanium plate and screws with hyomandibular suspension on hypopharyngeal airway dimensions. It is an anatomical feasibility study performed using 10 human cadaver heads.

Methods: The hyoid bone is trifurcated. The expanded hyoid is then suspended to the mandible. Computed tomography (CT) scans were performed on the cadavers to measure the airway dimensions before and after the procedure.

Results: This procedure resulted in statistically significant increase in airway dimensions at the level of the hypopharynx in all 10 human cadaver heads. Increase in cross-sectional area correlated significantly with increase in 3-dimensional (3D) volume.

The mean area of the airway at the level of the hyoid increased from $999.3 \pm 193.0 \text{ mm}^2$ to $1241.4 \pm 103.2 \text{ mm}^2$. Statistically significant increase in upper airway volume based on 3D reconstruction was also noted. Upper airway volume increased from $6.94 \pm 6.46 \text{ mL}$ to $13.58 \pm 8.29 \text{ mL}$.

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Conclusion: Airway dimensions increased with hyoid expansion and hyomandibular suspension in our cadaveric study measured using CT scans. Further studies are needed to see if this technique can be translated to clinical use in live patients.

Level of evidence: NA.

KEYWORDS

computed tomography, hyoid expansion, hyomandibular suspension, obstructive sleep apnoea

1 | INTRODUCTION

Obstructive sleep apnoea (OSA) is the most common sleep-related breathing disorder and is estimated to affect approximately 13% of men and 6% of women aged 30 to 70 years.¹ It is characterized by repetitive partial or complete obstruction of the upper airway during sleep due to abnormalities in pharyngeal anatomy, tone and physiology. These repeated disruptions of airflow result in chronic intermittent hypoxia, sympathetic over-activation and sleep fragmentation. Apart from resulting in excessive daytime somnolence, impaired cognitive function and reduced quality-of-life, untreated OSA is associated with metabolic syndrome and an increased risk of cardiovascular events, stroke and death.^{2,3}

The gold-standard treatment of OSA is continuous positive airway pressure (CPAP) therapy. However, not all patients are able to tolerate lifetime nightly use. Even in patients who choose CPAP therapy, actual compliance data has been shown to be only approximately 50% of the ideal.⁴

Surgical reconstruction of the upper airway is an option for patients who have been unsuccessful with CPAP. Several surgical procedures are used in the treatment of OSA, each designed to increase upper airway patency at specific levels such as the nasal cavity, velopharynx, tongue base and hypopharynx; each demonstrating mixed success and cure rates.⁵ Prior to surgical treatment, the site(s) of upper airway collapse is usually determined by either nasoendoscopy, cephalometry or drug induced sleep endoscopy. Collapse of the airway is usually multi-level⁶⁻⁸ and collapse at the hypopharyngeal level is a challenging area to address with no ideal surgery identified at the moment.⁹

The hyoid bone is a horse-shoe shaped bone in the anterior midline of the neck and forms the point of attachment for various muscles of the floor of mouth, tongue and pharynx. Due to these muscular attachments, the hyoid is closely related to pharyngeal airway dimensions. The geniohyoid and aponeurotic fibres of the genioglossus are attached to the hyoid body. Contraction of these muscles during inspiration causes anterior movement of the hyoid and resultant increase in the anteroposterior (AP) dimension of the retrolingual hypopharynx, thereby contributing to the maintenance of upper airway patency. Multiple cephalometric studies have shown that the hyoid bone is more inferior and posterior in OSA patients,¹⁰⁻¹² predisposing to pharyngeal wall collapse and obstruction at the retrolingual hypopharynx. In addition, shorter AP length or lateral width of the hyoid bone¹³ and longer distance between the hyoid and mandible have been shown to be associated with more severe OSA.^{14,15}

Recognizing the relation of the hyoid to hypopharyngeal airway dimensions, surgical procedures have been developed to augment and stabilize the hyoid. These procedures include hyomandibular suspension, hyoidthyroidpexia and hyoid expansion. The concept of hyoid expansion was first described by Patton et al¹⁶ in a live canine model and pressure-volume studies showed consistent expansion of the superior hypopharynx with resultant increase in airflow and decrease in closing pressure in that study. Riley et al¹⁷ first described hyoid suspension to the mandible as part of a multilevel surgical strategy for OSA. Since then, various methods of hyoid suspension have been described (hyoidthyroidpexia, hyoid myotomy, and suspension) with varying success rates reported.¹⁷⁻²⁰

It is hypothesized that coupling hyoid expansion with additional hyomandibular suspension will increase the dimensions and stability of the upper airway at the hypopharyngeal level to a greater degree than hyoid suspension alone. This cadaveric study was performed to evaluate the anatomical and technical feasibility of hyoid expansion using titanium plates and screws with hyomandibular suspension on hypopharyngeal airway area and volume using Computed Tomographic (CT) comparative analysis.

2 | METHODOLOGY

This is a cadaveric study approved by the Singapore General Hospital Institutional Review Board. The study was performed in a dissection laboratory using 10 adult human cadavers. Demographical data of the cadavers were not available. All specimens had intact mandible, hyoid and neck. The specimens were checked to ensure that no prior upper airway or neck surgery had been performed. The specimens were allowed to thaw completely before the pre-dissection baseline CT was performed. Pre and post-dissection CT scans were performed within the same day to minimize the impact of soft tissue degradation on airway measurements.

2.1 | Hyoid expansion and hyomandibular suspension

A horizontal skin incision was made directly over the hyoid bone through the subcutaneous layer and platysmal muscle. The skin and subplatysmal planes were raised to expose the inferior border of the

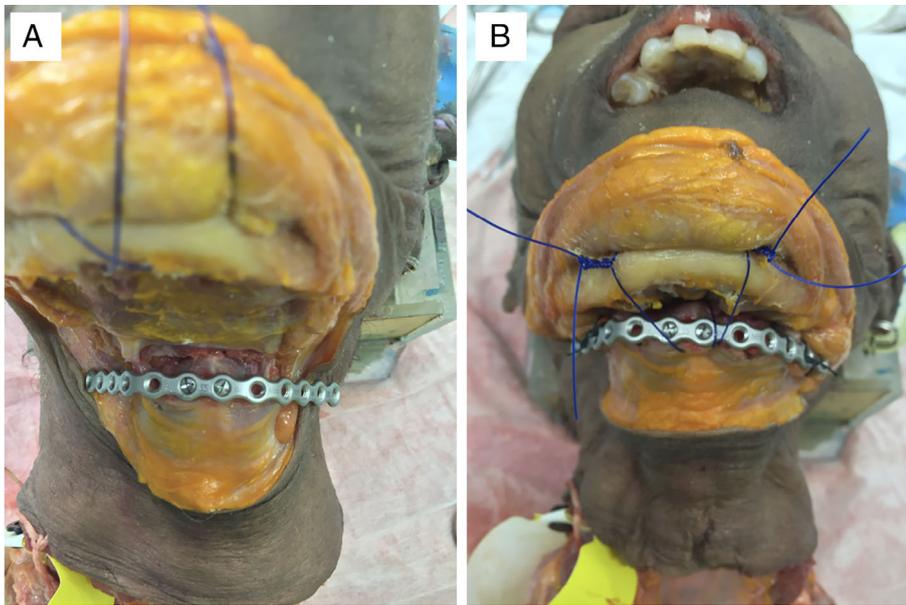


FIGURE 1 A, Hyoid expansion using titanium plate and screws. B, Expanded hyoid suspended to mandible using Prolene 1-0 sutures

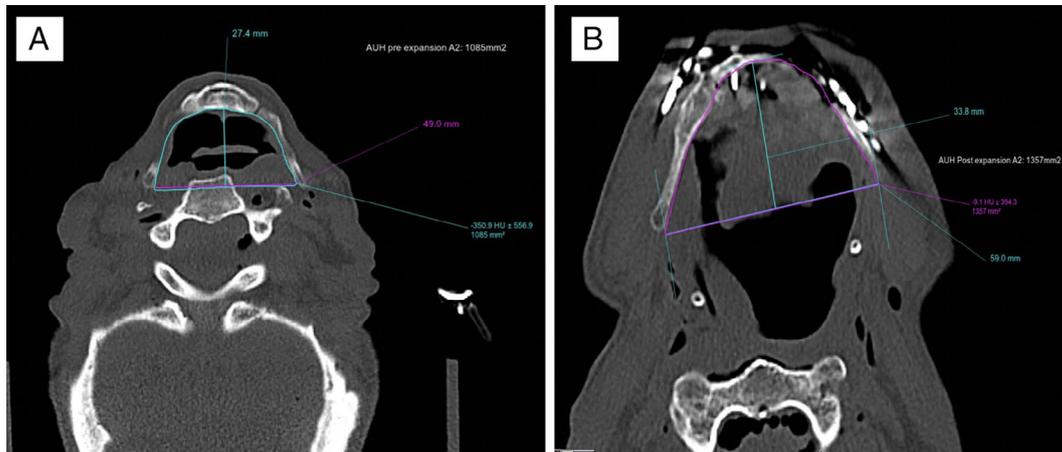


FIGURE 2 Computed tomography images of anteroposterior and lateral diameters of hypopharyngeal airway before, A, and after, B, hyoid expansion with hyomandibular suspension

mandible and the anterior aspect of the hyoid bone. Excessive deep dissection was avoided over the superior and posterior aspects of the hyoid body to ensure that the genioglossus and geniohyoid attachments were not removed and the hyoepiglottic ligament was not damaged. Cuts were then made with a bone-cutter medial to the lesser cornu on each side to tri-fracture the hyoid bone. A 12-hole titanium adaption plate (AO Synthes Compact 2.0 System) was then bent into the shape of the hyoid. The lateral segments (with greater cornu) were distracted from the hyoid body and the tri-fractured complex was reconstructed with the titanium plate and 1.3 mm self-tapping 6 mm screws. A 2-drill-hole length was achieved between each segment in all specimens.

Next, 2 holes are drilled through the inferior border of the body of mandible and the expanded hyoid was suspended anterosuperiorly to the mandible using Prolene 1-0 sutures (Figure 1).

2.2 | CT analysis of airway dimension and volume

Multidetector CT scans (SOMATOM Definition Flash, Siemens, Erlangen, Germany) of the neck were performed before and after the aforementioned surgical procedures, and reconstructed at fine 1 mm thickness at 0.6 mm interval. The images were then sent to a dedicated workstation at the 3D laboratory in Department of Diagnostic Radiology, Singapore General Hospital for post processing and data analysis by VitreaCore (version 6.7.4) advanced application software. All 2D measurements (maximum AP and Lateral), area under hyoid bone and 3D volumetric data of the airway were calculated in both pre and post procedure (Figures 2 and 3).

A semiautomatic segmentation method using Vitrea Advanced tool “laryngeal airway” was selected and “seed and grow method” was used in all 3 planes using Housefield Units (HU values) to

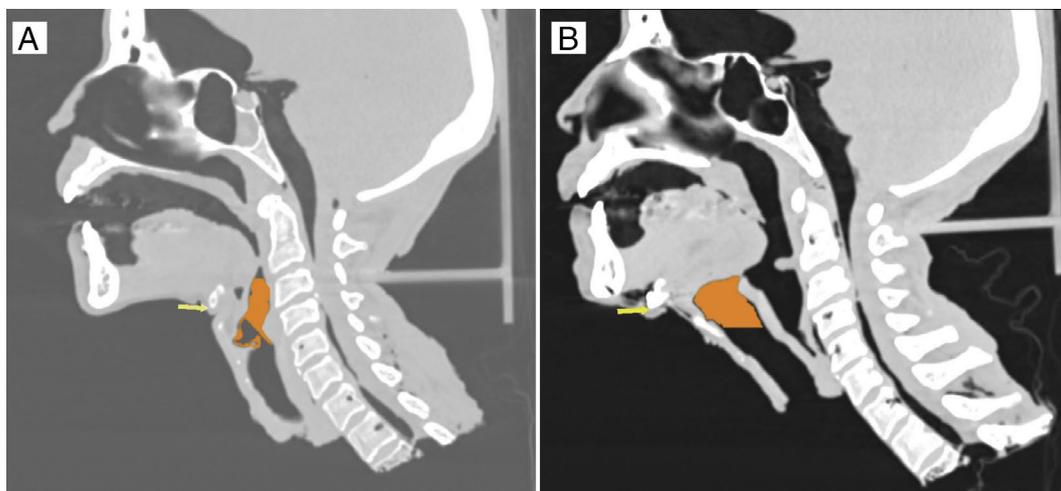


FIGURE 3 Computed tomography images of hypopharyngeal airway volume before, A, and after, B, hyoid expansion with hyomandibular suspension

TABLE 1 Hypopharyngeal airway diameter before and after hyoid expansion with hyomandibular suspension using Computed Tomographic comparative analysis

Cadaver	Pre-expansion			Change in area (mm ²)	Post-expansion		Difference (Post - Pre)	
	AP (mm)	Lateral (mm)	Ratio AP:lateral		AP (mm)	Lateral (mm)	AP (mm)	Lateral (mm)
1	39.9	33.7	1.18	+8	40.5	31.7	+0.6	-2.0
2	27.4	49.0	0.56	+272	33.8	59.0	+6.4	+10.0
3	40.8	33.8	1.21	+542	43.9	53.6	+3.1	+19.8
4	33.4	43.0	0.78	+435	39.2	50.4	+5.8	+7.4
5	28.9	38.1	0.76	+62	27.3	45.2	-1.6	+7.1
6	29.1	47.7	0.61	+105	27.4	59.7	-1.7	+12.0
7	32.3	34.9	0.93	+106	25.1	50.5	-7.2	+15.6
8	34.3	45.1	0.76	+279	39.7	44.3	+5.4	-0.8
9	36.0	50.1	0.72	+368	31.9	65.9	-4.1	+15.8
10	31.5	29.7	1.06	+244	29.0	47.0	-2.5	+17.3

Abbreviation: AP, anteroposterior.

TABLE 2 Hypopharyngeal airway area before and after hyoid expansion with hyomandibular suspension using computed tomographic comparative analysis

Cadaver	Pre-expansion area (mm ²)	Post-expansion area (mm ²)	Change in area (mm ²)	% change in area
1	1108	1116	+8	0.7
2	1085	1357	+272	25.1
3	1280	1822	+542	42.3
4	1074	1509	+435	40.5
5	826	888	+62	7.5
6	877	982	+105	12.0
7	824	930	+106	12.9
8	1012	1291	+279	27.6
9	1229	1597	+368	29.9
10	678	922	+244	36.0
Mean	999.3 (SD 193.0)	1241.4 (SD 326.2)	+242.1 (+118.2 to + 366.0; P = .002)	23.5 (SD 14.5)

TABLE 3 Hypopharyngeal airway volume before and after hyoid expansion with hyomandibular suspension using computed tomographic comparative analysis

Cadaver	Pre-expansion volume (ml)	Post-expansion volume (ml)	Change in volume (ml)
1	2.37	7.80	+5.43
2	22.66	26.53	+3.87
3	4.46	19.01	+14.55
4	10.73	18.82	+8.09
5	0.69	1.08	+0.39
6	3.08	7.88	+4.80
7	8.28	13.87	+5.59
8	1.58	7.53	+5.95
9	7.02	24.28	+17.26
10	8.50	8.98	+0.48
Mean	6.94 (SD 6.46)	13.58 (SD 8.29)	+6.64 (+2.73 to +10.55; $P = .004$)

TABLE 4 Correlation of distance between lesser cornu of the hyoid bone, change in area and change in volume after hyoid expansion with hyomandibular suspension

Cadaver	Distance between lesser Cornu (mm)		Change in area (mm ²)	Change in volume (ml)
	Pre-expansion	Post-expansion		
1	22.0	26.0	+8	+5.43
2	22.0	23.7	+272	+3.87
3	22.0	28.8	+542	+14.55
4	22.2	29.0	+435	+8.09
5	22.1	29.0	+62	+0.39
6	21.9	26.6	+105	+4.80
7	22.0	30.0	+106	+5.59
8	21.3	32.0	+279	+5.95
9	22.4	28.0	+368	+17.26
10	18.7	25.5	+244	+0.48

obtain 3D airway volumetric data under the hyoid bone as well as of hypopharyngeal airway up to vocal cords, along its long axis and displayed in all 3 planes. For volumetric analysis, the lower plane was fixed at the level of vocal cords, while the upper plane was fixed at a line drawn from genial tubercle of mandible to the posterior-inferior corner of the C2 vertebra of the cervical spine, in both pre and post-procedure CT scans. The upper level for calculating the volume was predefined as the expanded hyoid bone was suspended antero-superiorly closer to the mandible. Once segmented, the 3D volumetric data of the pharyngeal airway were again refined using contour editing tool to obtain true shape of the selected airway by eliminating unwanted tissue and surgical emphysema. Finally, without any significant variations in post-processing and using strict pre-defined landmarks, automated

volume was generated for all pre and post-procedural hypopharyngeal airway.

2.3 | Statistical analysis

Statistical analyses were performed using IBM SPSS version 25.0 (IBM Inc). All mean values were shown as mean (SD). Differences in the value of mean with the appropriate 95% confidence interval were shown using a paired-sample test. Correlation between variables were shown using Pearson test. A P value of $<.05$ was considered statistically significant.

3 | RESULTS

This procedure resulted in statistically significant increase in airway dimensions at the level of the hypopharynx in all 10 human cadaver heads. The pre and post-procedure AP and lateral measurements are shown in Table 1. The mean (SD) area of the airway at the level of the hyoid increased from 999.3(193.0)mm² pre-expansion to 1241.4 (103.2)mm² post-expansion, with a resultant average increment of 242.1mm² ($P = .002$) (Table 2). Statistically significant increase in upper airway volume based on 3D reconstruction was also noted. Mean (SD) upper airway volume increased from 6.94(6.46)ml pre-expansion to 13.58(8.29)ml post-expansion, with a resultant increment of 6.64 ml ($P = .004$) (Table 3). It was also found that cases with greatest increase in cross-sectional area correlated significantly with a greater increase in 3-dimensional (3D) volume ($r = .666$, $P = .035$).

The shape of the hyoid bone as determined by its AP:lateral dimension ratio did not significantly affect the amount of area ($P = .832$) or volume ($P = .720$) that could be expanded. Distance between the lesser cornu of the hyoid bone also did not significantly affect post-expansion area ($P = .932$) or volume ($P = .170$) (Table 4).

4 | DISCUSSION

An inferiorly displaced hyoid as measured by an increased mandibular plane to hyoid distance on lateral cephalometry has been one of the anatomical features most commonly associated with OSA.²¹ Multiple surgical procedures, as described above, aim to displace the hyoid forwards and upwards by fixing it to an anatomical structure such as the mandible or thyroid cartilage. Reported rates of improvement with hyoid surgery varied widely from 22% to 77%.²² A recent meta-analysis reviewing patients who underwent hyoid surgery alone for the treatment of OSA reported a reduction of 38.3% in apnoea-hypopnoea index (AHI) overall. AHI reduced by 38.3% for hyoid myotomy and suspension; 50.7% for hyothyroidopexy; and by 7.1% for hyoid expansion.²³

The concept of hyoid expansion was first reported by Patton et al¹⁶ who performed expansion hyoidplasty on 20 live canines by tri-fracturing the hyoid bone and holding the expanded segments in

place with arch bars and wires. Postprocedure pressure-volume studies showed consistent expansion of the superior hypopharynx with increase in airflow and decrease in closing pressure. Deglutition and laryngeal competence were not grossly affected. Since then, the only study reporting outcomes after hyoid expansion in humans was by Hamans et al.²⁴ This group performed hyoid expansion using an implantable Air-frame device to cause 10 mm lateral expansion of the hyoid bone. Although this procedure significantly improved snoring and daytime sleepiness, the results did not clinically support hyoid expansion for treatment of OSA as there was no objective improvement of AHI. This lack of clinical efficacy was postulated to be due to the inability to select patients with true isolated hypopharyngeal lateral wall collapse using current diagnostic techniques. Upper airway dimensions were not measured in this study and another possible reason was that the procedure did not change upper airway dimensions at all, as it was restricted by the multiple muscular and ligamentous attachments to the hyoid.

The senior author of this study previously evaluated the effects of combined hyoid expansion and hyomandibular suspension on intraluminal hypopharyngeal airway dimensions using computer-assisted videoendoscopic measurement on fresh human cadavers.²⁵ The study showed that tri-fracturing the hyoid bone and stabilization with titanium plate and screws led to a statistically significant increase in the 2-dimensional hypopharyngeal airway size measured at the retroglossal area which was further augmented with hyomandibular suspension.²⁵ However, the amount of increase in airway dimensions was not consistent across cadavers and hypopharyngeal airway volume was not assessed.

In this cadaveric study, we were able to demonstrate an increase in airway cross-sectional dimensions at the level of the hyoid (from $999.3 \pm 193.0 \text{ mm}^2$ to $1241.4 \pm 103.2 \text{ mm}^2$) and hypopharyngeal airway volume (from $6.94 \pm 6.46 \text{ mL}$ to $13.58 \pm 8.29 \text{ mL}$) in all cadavers post-procedure. Two-dimensional airway expansion at the level of the hyoid consistently resulted in an increase of hypopharyngeal airway volume. However, the degree of expansion was not consistent across cadavers. Although we were able to achieve a 2-drill-hole length expansion anteriorly between each segment of the hyoid in all cadavers, this did not result in consistent expansion of the lateral dimensions (distance between greater cornu) posteriorly. In some cadavers, lateral hyoid expansion resulted in a reduction of the AP dimension airway. Hyoid shape, as quantified by the AP:lateral ratio, was not found to be a useful predictor of eventual expansion outcome.

The hyoid is unique in that it does not articulate with any other bones but is instead suspended by various muscles and ligaments. The attachment of the hyoglossus and the middle constrictor would create an opposing force to lateral expansion and could cause the greater cornu to tilt and rotate inwards despite anterior expansion of the hyoid segments. This could explain the inconsistent expansion results achieved despite ensuring a fixed amount of anterior expansion of the segments. Age and previous disease processes of the different cadavers could also affect the soft tissue consistency and could also account for differences in achievable expansion.

Due to the easy accessibility of the hyoid, there were relatively few technical difficulties encountered. One difficulty noted was that

the lateral hyoid segments were too thin in certain cadavers to allow screw fixation. In these cases, the lateral hyoid segment was secured to the titanium plate by Prolene 1-0 suture.

5 | LIMITATIONS

Our study has several limitations. The lack of soft tissue muscle tone in cadavers may not allow direct extrapolation of our results to live humans. Second, the cadavers had differences in age, size, gender, and ethnicity, which could also account for the variability in expansion results. Furthermore, the important effect of our procedure on appearance and deglutition could not be studied.

Further studies are required to investigate if this technique can be translated to clinical use in live patients.

6 | CONCLUSION

Airway dimensions significantly increased with hyoid expansion and hyomandibular suspension in our cadaveric study measured using CT scans. Further studies are needed to see if this technique can be translated to clinical use in live patients.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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