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SCIENTIFIC INVESTIGATIONS

Swallowing biomechanics before and following multi-level upper airway surgery for obstructive sleep apnea

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Study Objectives: The effect of contemporary multi-level upper airway surgery for obstructive sleep apnea on swallowing is unclear. This study assessed the biomechanical swallowing function in participants with obstructive sleep apnea pre- and post-modified uvulopalatopharyngoplasty and coblation channeling of the tongue.

Methods: In this prospective, longitudinal study, adults diagnosed with moderate-severe obstructive sleep apnea who underwent modified uvulopalatopharyngoplasty and coblation channeling of the tongue surgery had swallowing biomechanics assessed using high-resolution pharyngeal manometry and analyzed with swallowgateway.com. Symptomatic swallowing difficulty was evaluated using the Sydney Swallow Questionnaire (≥ 234). General linear mixed-model analysis was conducted to evaluate the difference pre- and post-modified uvulopalatopharyngoplasty and coblation channeling of the tongue. Data are presented as mean [95% confidence intervals].

Results: High-resolution pharyngeal manometry assessments were conducted in 10 participants (7 men; median age 50 [interquartile range 36–65]) preoperatively and repeated postoperatively at 9 months [interquartile range 6–13]. Self-reported dysphagia was unchanged following surgery (Sydney Swallow Questionnaire =149 [53, 447] to 168 [54, 247]; *P* = .093). High-resolution pharyngeal manometry outcomes indicated reduced mesopharyngeal pressures (148 [135, 161] to 124 [112, 137] mm Hg s cm; *P* = .011), reduced hypopharyngeal pressures (113 [101, 125] to 93 [84, 102] mm Hg s cm; *P* = 0.011), and reduced upper esophageal sphincter relaxation pressure (5 [4, 6] to 2 [1,3] mm Hg; *P* = 0.001) but no change to velopharyngeal pressures (135 [123, 147] to 137 [117, 157] mm Hg s cm; *P* = .850) postsurgery.

Conclusions: Modified uvulopalatopharyngoplasty may have less implications on the swallow mechanism than previously suspected. In contrast, the reduction in mesopharyngeal contractile pressures associated with coblation channeling of the tongue, although within normal limits, may affect bolus propulsion. Biomechanical alterations were insufficient to worsen self-reported swallowing function.

Keywords: deglutition disorders, sleep-disordered breathing, manometry, patient-reported outcome measures, upper airway physiology

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BRIEF SUMMARY

Current Knowledge/Study Rationale: Disordered swallowing is a reported complication following the surgical management of obstructive sleep apnea. However, limited comparison to presurgical swallow function and increasing recognition of subclinical dysphagia in people with obstructive sleep apnea raise uncertainty regarding the effect of surgery on swallowing. Therefore, this study assessed the swallowing biomechanics in participants with obstructive sleep apnea pre- and post-modified uvulopalatopharyngoplasty and coblation channeling of the tongue.

Study Impact: This study identified biomechanical pharyngeal and upper esophageal sphincter changes following modified uvulopalatopharyngoplasty and coblation channeling of the tongue surgery for obstructive sleep apnea; however, self-reported swallowing symptoms did not differ. These novel findings provide insight into effect of modified uvulopalatopharyngoplasty and coblation channeling of the tongue on the swallow mechanism, contributing to the understanding of side effects for those people with obstructive sleep apnea whereby surgical management is the alternative treatment.

INTRODUCTION

Obstructive sleep apnea (OSA) is a highly prevalent, chronic disease characterized by recurrent upper airway obstructive episodes during sleep.[1,2] Untreated OSA is associated with increased morbidity and mortality.[3,4] The pathophysiology of OSA is heterogenous, which has implications for tailoring treatment.[5–7] Continuous positive airway pressure therapy is considered the first-line treatment for maintaining airway patency in OSA management.[8] However, reduced adherence or inability to use continuous positive airway pressure[9] is an ongoing issue that impedes the possible health benefits.[10]

Surgery to remodel and stabilize the upper airway is an accepted treatment following failure to tolerate or accept long-term continuous positive airway pressure therapy.[11,12] However, international consensus regarding criteria for surgery is lacking. A wide range of surgical procedures for the management of OSA exist. In our center, modified uvulopalatopharyngoplasty and coblation channeling of the tongue (mUPPP+CCT) is used in patients with moderate-severe OSA who are unable to tolerate or adhere to medical device use and who have at least 25% collapse (loss of the airspace seen on video endoscopy) at multiple levels, including the velum, tonsils, and tongue base. This approach minimizes excessive velopharyngeal and uvula tissue removal to reduce postsurgical morbidity and ablates tissue columns to reduce tongue volume.[13] A recent multicenter randomized control trial reported significant reduction in the severity of OSA and daytime sleepiness symptoms following mUPPP+CCT surgery.[14]

Disordered swallowing (dysphagia) is one of several complications reported following the surgical management of OSA, with an incidence ranging between 18 and 27%.[15,16] The prevalence of postsurgical dysphagia, like other complications, has reduced since contemporary surgical techniques have replaced more traditional surgical techniques.[16,17] Findings from videofluoroscopic swallowing studies (VFSS), which is considered a gold standard assessment of swallow function, have reported premature spillage, laryngeal penetration and/or aspiration, and pharyngeal residue following surgery.[18–21] However, most reports lack a presurgical baseline assessment,[16] which is an important limitation given that dysphagia is also commonly reported in people with OSA.[22] Two studies that have compared presurgical and postsurgical swallowing using VFSS reported only minimal changes in swallowing outcomes.[23,24] However, this mode of assessment may be insufficient to detect subtle changes in swallowing efficacy.

High-resolution pharyngeal manometry (HRPM) is an emergent technology that quantifies the biomechanical generated pressure sequence during the pharyngeal swallow. Associated bolus transport and luminal distension is measured by combining HRPM with intraluminal impedance.[25] Validity[26] and reliability[27] have been demonstrated with the interpretation of HRPM analysis. HRPM enables detection of subtle changes of swallowing physiology, which can be compared with normative data ranges.[28,29] This allows precise characterization of the mechanisms contributing to dysphagia. Our group used this new assessment to detect impaired upper esophageal sphincter (UES) relaxation and opening in people with OSA, both without surgical intervention and following mUPPP+CCT.[30,31] However, pre- vs post-upper airway surgery comparisons have not been investigated. Thus, the precise effect of mUPPP+CCT on swallowing function remains unclear. We therefore undertook a prospective study to assess swallowing symptoms and biomechanical swallowing function in participants with OSA before and after mUPPP+CCT.

METHODS

Participants

Ethical approval was granted by the Southern Adelaide Clinical Human Research Ethics Committee (Approval No. 283.11 and 156.18). Patients were invited to participate and provided written informed consent. Prospective enrolment occurred consecutively between November 2017 and November 2019.

Participants were recruited from the practice of Otolaryngology Head and Neck surgeons at Flinders Medical Centre and Flinders Private Hospital. Inclusion criteria: adult (> 18 years), planned for mUPPP+CCT for the management of moderate-severe OSA (apnea hypopnea index [AHI] > 15 events/h sleep,[2] based on an overnight polysomnography sleep study, either type 1 or 2). Exclusion criteria: other pharyngeal or gastrointestinal surgery, reflux, allergy to local anesthesia, pregnancy, uncontrolled diabetes or blood pressure, or neurological diagnosis.

Surgical technique

Presurgery the tonsil size and palate position were graded using the Friedman staging system.[32] The mUPPP+CCT surgery was performed by 2 consultant surgeons experienced with this procedure in a standard manner as published.[13,14] The mUPPP surgical protocol comprises of bilateral tonsil (if tonsils are present) and supratonsillar fat resection, division of posterior pillar mucosa and musculature at the junction of upper third/lower two-thirds, advancement of the upper part of the posterior pillar musculature into the superolateral velopharyngeal port, and 50–75% resection of the uvula to create a neo-uvula. The CCT protocol involves the use of a Reflex SP plasma wand (Arthrocare Corp, Austin, TX) at a power setting of 6, for 15 s per channel. Channels (7 to 9) were created along the anterior tongue, comprising 3 to 5 midline channels and up to 2 lateral channels on each side.

Patient-reported outcome measures

Patient-reported symptom questionnaires were completed prior to surgery and repeated 6 months following surgery. The Epworth Sleepiness Scale, a validated self-reported questionnaire, was used to assess daytime sleepiness.[33] An Epworth Sleepiness Scale ≥ 10 was considered indicative of symptomatic daytime sleepiness. The Sydney Swallow Questionnaire (SSQ), a validated 17-item patient-reported outcome measure of symptomatic dysphagia using a visual analog scale rating of symptoms,[34,35] was completed by all participants at the time of HRPM investigations. An SSQ ≥ 234 was considered indicative of symptomatic dysphagia.[34]

HRPM assessment

HRPM swallow assessments were conducted prior to surgery and 6–12 months following surgery. An 8-French catheter with 32 pressure sensors (unidirectional) and 16 impedance transducers (Unisensor AG catheter, Atticon, Switzerland) was used. Following a 4-hour fast, lignocaine spray (5%) was topically administered to the nose. The catheter was inserted *trans*-nasally and positioned spanning the velopharynx and proximal esophagus. Pressure and impedance data were acquired at 20 samples per second using the Solar GI acquisition unit (Medical Measurement System, Enschede, The Netherlands). During the assessment, participants were seated upright with their head in a neutral position. Following a 5-minute accommodation period, a total of 18 bolus swallows were administered via syringe comprising 3 swallows of 5, 10, and 20 mL thin and extremely thick liquids. Preparation of the tested boluses utilized the standardized HRPM bolus medium (SBMkit, Trisco Foods Pty Ltd, Brisbane, Australia)[28] with 100 mL of tap water. The tested bolus viscosity was compliant with the International Dysphagia Diet Standardization Initiative (IDDSI; International Dysphagia Diet Standardization Initiative 2019, https://iddsi.org/framework) with thin liquids and extremely thick liquids consistent with IDDSI 1 and 4, respectively.

Analyses of the HRPM data was initially conducted by an experienced speech pathologist and reviewed by an expert in HRPM analysis using the online application Swallow Gateway (swallowgateway.com, version 2020; Flinders University, Adelaide, Australia). Single swallows were chosen by drawing a region of interest box highlighting the velopharynx to the inferior border of the proximal esophagus. Anatomical markers were placed, including at the velopharynx and hypopharynx and UES, as well as timing markers of UES relaxation and closure.[31]

Output from the Swallow Gateway analysis application included the 8t HRPM core metrics and 6 additional outcome metrics (**Table 1**) consistent with the recommendations of the International HRPM Working Group.[25] The Swallow Risk Index was determined as an additional global measure of swallowing. Swallow Risk Index is a composite score derived from 4 metrics (bolus presence time, distension-contraction latency, intrabolus pressure, and mean hypopharyngeal peak pressure) and is a validated broad indicator level of swallowing dysfunction with a Swallow Risk Index cut value of 15 or more predisposing an increased aspiration risk.[26,27]

Statistical analysis

The average results for each of the 6 swallow test conditions were analyzed using SPSS (IBM Corp. IBM Statistical Package for the Social Sciences [SPSS] Statistics for Windows, v. 26.0 Armonk, NY). HRPM data with a skewed distribution were normalized by log transformation prior to analysis. The main effects of surgery (time point) and baseline dysphagia on swallow biomechanics were determined using generalized linear mixed model whereby timepoint, volume, and viscosity were included as repeated measures. GLMM statistics (F, *P* value) were used to quantify and compare main effects. Patient-related outcome variables were compared presurgery and postsurgery using Wilcoxon signed-rank test. Data are otherwise presented as median (interquartile range).

RESULTS

Demographics

Presurgical and postsurgical data were available for all 10 study participants. The median time for postsurgical HRPM assessment was 9 months, ranging from 6 to 13 months. Group demographics are presented in **Table 2**. Prior to surgery, 7 participants had a diagnosis of severe OSA (AHI > 30 events/h sleep) and 3 had moderate OSA (AHI between 15 and 30 events/h sleep). Excessive daytime sleepiness was reported in 3 participants (Epworth Sleepiness Scale > 9). The median BMI value was 31 kg/m^2 (indicating an obese cohort). Prior to surgery, 2 participants had absent tonsils. Of the remaining 8 participants, there was a tonsil size median grade 3 [3,3],[32] palate position modified Mallampati median grade 2 [1.5, 2.5], with corresponding Friedman stage median 1 [1, 2][32] (**Table 2**).

Postoperative polysomnography was conducted at 3–6 months in 7 participants, with 3 participants declining polysomnography due to improvement in sleepiness symptoms. Although the total AHI and the ESS values tended to decrease following surgery (**Table 2**), statistical significance was not demonstrated ($P = .091$ and $P = .058$, respectively).

Patient-reported outcome measures of swallowing

There was no significant change in median total SSQ scores following surgery (presurgery 149 [53, 447] vs postsurgery 168 [54, 247], $P = .093$, **Figure 1**). 70% (n = 7) of participants did not have dysphagia symptoms (SSQ ≥ 234) at postsurgery follow-up.

The 3 participants with presurgery dysphagia had a reduction in symptoms postsurgery, but 2 participants remained above the dysphagia score threshold (SSQ ≥ 234).

HRPM outcome metrics

All participants tolerated the HRPM investigations, although 2 participants were unable to consume 20 mL extremely thick liquid bolus due to self-reported fullness. The main effects of mUPPP+CCT on HRPM core and additional outcome metrics are shown in **Table 3**.

Pharyngeal contractile integrals (velo-, meso-, hypo-)

A representative participant example showing pre- and post-mUPPP+CCT is provided in **Figure 2**. Overall, velopharyngeal contractility did not change following surgery (**Table 3**). There was a significant reduction of the mesopharyngeal contractility (MCI, $P = .01$, **Table 3**, **Figure 3**) and the hypopharyngeal contractility ($P = .01$, **Table 3**) following mUPPP+CCT. Pairwise comparisons showed that the reduction of the mesopharyngeal contractility was most pronounced during 20 mL swallows ($P < .05$, **Table 3**). Total pharyngeal contractility tended to reduce following the surgery without reaching statistical significance ($P = .09$, **Table 3**).

Hypopharyngeal intrabolus distension pressure

The hypopharyngeal intrabolus pressure did not differ pre- and post-mUPPP+CCT ($P = .11$, **Table 3**).

UES relaxation and opening

UES relaxation pressure (UES IRP) was significantly reduced following mUPPP+CCT ($P = .001$, **Table 3**, **Figure 2**, and **Figure 4**). Pairwise comparisons were significant for 5 and 10 mL volumes and thin (IDDSI 0) and thick (IDDSI 4) fluid consistencies ($P < .05$, **Table 3**). UES relaxation time (UES RT) and UES opening extent (UES maximum admittance) did not differ following the surgery ($P = .192$ and $P = 0.67$, respectively, **Table 3**).

Table 1—High-resolution pharyngeal manometry core and additional outcome metrics and definitions.[25]

Measurement	Definition
HRPM Core Outcome Metrics	
Pharyngeal lumen occlusive pressure	
Pharyngeal contractile integral	An integral pressure measure of pharyngeal contractile vigor spanning from the velopharynx to the upper margin of the UES (mm Hg cm s).
Velopharyngeal contractile integral	An integral pressure measure of pharyngeal contractile vigor spanning the velopharyngeal region only (mm Hg cm s).
Mesopharyngeal contractile integral	An integral pressure measure of pharyngeal contractile vigor spanning the mesopharyngeal region only (mm Hg cm s).
Hypopharyngeal contractile integral	An integral pressure measure of pharyngeal contractile vigor spanning the hypopharyngeal region only (mm Hg cm s).
Hypopharyngeal intrabolus distension pressure	
IBP	The pressure 1 cm superior to the UES apogee position at the time of maximum hypopharyngeal distension (indicated by impedance/admittance) (mm Hg).
UES relaxation & opening	
UES integrated relaxation pressure	A pressure measure of the extent of UES relaxation pressure, generated as the median of the lowest pressure in a nonconsecutive 0.20-second to 0.25-second window (mm Hg).
UES relaxation time	A measure of the duration of UES relaxation—a pressure interval below 50% of baseline or 35 mm Hg, whichever is lower, in units of seconds (s).
UES maximum admittance	A measure of extent of UES opening. The highest admittance value (inverse of impedance) recorded during *trans*-sphincteric bolus flow, in units of millisiemens (mS).
HRPM Additional Outcome Metrics	
Global swallow function	
SRI	A composite score based on a mathematical formula comprising of four hypopharyngeal swallow metrics (IBP, BPT, DCL, peak pharyngeal pressure) providing a numerical value distinguishing normal from abnormal swallow function (SRI > 15 indicates abnormal function).
Timing measures	
BPT	Duration of the bolus in the hypopharynx prior to UES relaxation—a correlate of the dwell time of the bolus in the pharynx (s).
DCL	A timing measure from maximum pharyngeal bolus distension to the pharyngeal luminal occlusive contraction—a correlate of bolus propulsion ahead of the pharyngeal stripping wave (s).
UES preswallow and postswallow and proximal esophageal measures	
UES basal pressure	The peak pressure at the level of the UES preswallow (mm Hg).
UES contractile integral	An integral pressure measure of UES contractile vigor, post swallow (mm Hg cm s).
Proximal esophageal contractile integral	An integral pressure measure of proximal esophageal contractility (mm Hg cm s).

BPT = bolus presence time (BPT), DCL = distension-contraction latency, IBP = hypopharyngeal intrabolus distension pressure, SRI = Swallow Risk Index (SRI), UES = upper esophageal sphincter.

Additional HRPM outcome measures

The Swallow Risk Index reduced following surgery ($P = .01$, Table 3). Pairwise comparisons were significant for 20 mL volume and thick (IDDSI 4) fluid consistency ($P < .05$, Table 3). Bolus presence and timing measures (bolus presence time and distension-contraction latency) were unchanged following surgery. UES preswallow pressures (UES basal pressure), UES postswallow pressures (UES contractile integral), and the proximal esophageal contractile integral pressures (Prox Es) were unchanged following surgery (Table 3).

DISCUSSION

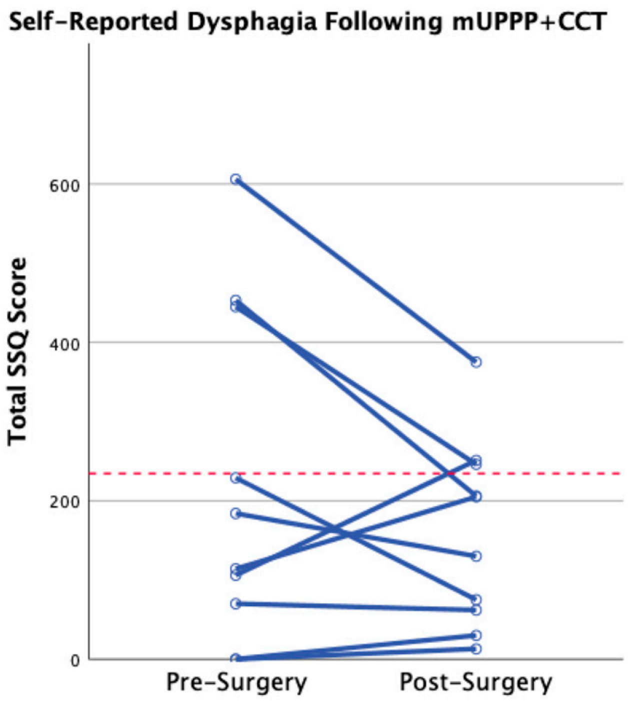
This is the first study to employ HRPM swallow assessments to evaluate swallowing function following mUPPP+CCT surgery for people diagnosed with moderate-severe OSA. The main biomechanical findings following mUPPP+CCT were: 1) pressures during velopharyngeal contraction were unchanged, 2) pressures during mesopharyngeal and hypopharyngeal contraction were reduced, and 3) pressures during UES relaxation were reduced. The velopharyngeal findings suggest that the mUPPP surgery did

Table 2—Participant demographics.

	Cohort (n = 10)	
1.	**Pre-Surgery**	**Post-Surgery**
Age (years)	50 [36–65]	-
Sex (male:female)	7:3	-
BMI (kg/m^2)	31 [27, 36]	-
Tonsil grade	2 [1,3]	-
Modified Mallampati grade	2 [2, 3]	-
Friedman staging	1 [1,3]	-
AHI	45 [29, 71]	26 [10, 72]
ESS	8.5 [6,11]	4 [2, 7]

Values are reported as median [interquartile range]. Tonsil size is graded from 0 to 4: 0, absent tonsils; 1, tonsils obscured by pillars; 2, tonsils visible at pillars; 3, tonsils extend beyond pillars but not to midline; 4, tonsils extend to midline. The palate-tongue position was categorized according to the modified Mallampati grade from 1 to 4[33]: 1, tonsils, anterior pillars, soft palate, and pharynx are visible; 2, uvula and superior pillars and tonsil visible; 3, soft and hard palate are visible; and 4, hard palate is visible. The Friedman staging combines tonsil size grade and palate-tongue position from stages 1 to 4.[32] Stage 1, modified Mallampati grades 1 or 2 with tonsil grades 3 or 4; Stage 2, modified Mallampati grades 1 or 2 with tonsil grade 1 or 2 or a palate grade 3 or 4 with a tonsil grade 3 or 4; Stage 3 palate grade 3 or 4 with tonsil grade 1 or 2; and Stage 4, BMI greater than 40. AHI = apnea-hypopnea index, BMI = body mass index, ESS = Epworth Sleepiness Scale.

Figure 1—Self-reported dysphagia symptoms represented by the total SSQ score pre- and post-mUPPP+CCT surgery of the 10 participants.



The red-dotted line located at 234 represents the cut-off value of symptomatic dysphagia. Following mUPPP+CCT surgery, 7 participants did not cross the cut-off value (represented by the red-dotted line); 3 participants showed a decrease in dysphagia symptoms (with 2 participants not crossing and 1 participant crossing the cut-off); and 1 showed an increase in dysphagia symptoms. mUPPP+CCT = modified uvulopalatopharyngoplasty and coblation channeling of the tongue, SSQ = Sydney Swallow Questionnaire.

not impair pressure generation at the velopharynx. The mesopharyngeal and hypopharyngeal findings suggest that the CCT technique may reduce force-generating capacity of these regions. While reduced, it is notable that the pressures remained within normal limits. The reduction in UES relaxation pressures may be an indirect result of reduced bolus propulsion due to reduced mesopharyngeal pressure generation. Participants overall did not report a change in dysphagia symptoms, suggesting that the biomechanical changes in swallowing function following mUPPP+CCT were insufficient to clinically impact swallowing.

OSA severity and self-reported sleepiness tended to decrease following mUPPP+CCT surgery, however did not reach statistical significance, likely due to the relatively small sample size for these outcomes. Indeed, the point estimates indicate a similar ~20 event/h reduction in AHI to the recently reported significant reductions in these outcomes from a larger randomized trial.[14] In addition, symptomatic dysphagia was unchanged postsurgery compared with presurgery. This is in line with a previous report[37] and is an important finding, as dysphagia has previously been described as a postoperative complication of OSA.[18–21] However, those studies lacked presurgical assessment for comparison. Recent investigations identified some people with OSA to have abnormal swallowing physiology without surgical treatment,[22] irrespective of whether they self-reported symptoms of dysphagia.[31,37] This raises the possibility of poor perception of swallowing function in people with OSA, which may be, at least in part, due to impaired pharyngeal sensation from OSA and/or pharyngeal surgery.[38]

Effects on velopharyngeal pressures

Although mUPPP surgery is a reconstructive technique that preserves the majority of the velum-free edges,[13] it involves a small degree of velar soft tissue resection. This has previously

Table 3—Biomechanical measures of swallowing pre- and post-mUPPP+CCT for management of moderate-severe OSA.

Metric	Pre-Surgery (n = 10)	Post-Surgery (n = 10)	Main Effects of Surgery
High-Resolution Pharyngeal Manometry Core Outcome Metrics			
Pharyngeal contractile integral (mm Hg cm s)	396 (374, 417)	361 (328, 395)	All conditions: $F = 2.852$, $P = .094$
Velopharyngeal contractile integral (mm Hg cm s)	135 (123, 147)	137 (117, 157)	NS
Mesopharyngeal contractile integral (mm Hg cm s)	148 (135, 161)	124 (112, 137)	All conditions: $F = 6.771$, $P = .011$* 20 mL volume: $F = 4.573$, $P = .035$*
Hypopharyngeal contractile integral (mm Hg cm s)	113 (101, 125)	93 (84, 102)	All conditions: $F = 6.713$, $P = .011$*
Intrabolus pressure (mm Hg)	7.57 (6.44, 8.70)	5.65 (3.54, 7.76)	All conditions: $F = 2.529$, $P = .115$
UES integrated relaxation pressure (mm Hg)	5.15 (3.84, 6.46)	2.18 (1.16, 3.19)	All conditions: $F = 12.615$, $P = .001$* 5 mL volume: $F = 2.666$, $P = .047$* 10 mL volume: $F = 3.581$, $P = .010$* Thin: $F = 6.060$, $P = .015$* Thick: $F = 6.557$, $P = .012$*
UES relaxation time (s)	0.55 (0.53, 0.57)	0.56 (0.53, 0.58)	NS
UES maximum admittance (mS)	5.21 (5, 5.38)	5.39 (5.18, 5.59)	All conditions: $F = 1.724$, $P = .192$
Additional High-Resolution Pharyngeal Manometry Outcomes			
Swallow Risk Index†	2.56 (2.18, 2.93)	1.83 (1.35, 2.31)	All conditions: $F = 6.909$, $P = .010$* 20 mL volume: $F = 5.913$, $P = .017$* Thick: $F = 6.112$, $P = .015$*
Bolus presence time (s)	0.62 (0.58, 0.65)	0.61 (0.57, 0.64)	NS
Distension-contraction latency (s)	0.48 (0.46, 0.50)	0.46 (0.43, 0.48)	All conditions: $F = 2.620$, $P = .108$
UES basal pressure (mm Hg)	74 (64, 84)	81 (69, 93)	NS
UES contractile integral (mm Hg cm s)	487 (437, 536)	515 (460, 570)	NS
Proximal esophageal contractile integral (mm Hg cm s)†	308 (283, 333)	372 (314, 430)	NS

Values are presented as mean (95% confidence intervals) and main effects of General Linear Mixed Modeling (GLMM) with *F* statistic and *P* values. Pairwise comparisons with Bonferroni adjustment presented presurgery and postsurgery for each bolus condition. *Significance ($P < .05$) pairwise comparisons of tested bolus conditions across volumes (5, 10, or 20 mL) and viscosity (thin [IDDSI 0] and extremely thick [IDDSI 4] liquids). †Measures were log transformed prior to GLMM. IDDSI = International Dysphagia Diet Standardization, NS = nonsignificant result, UES = upper esophageal sphincter.

been hypothesized to impede pharyngeal driving pressures[37] and reduce pharyngeal constriction times on VFSS.[24] In contrast, this HRPM analysis demonstrates that velopharyngeal contractile pressures were unaffected following surgery, suggesting that the mUPPP technique does not impair pressure generation at the velopharynx. Of note, while there was not a reduction in velopharyngeal pressures postsurgery, they did remain elevated compared to published normative ranges.[28] Higher velopharyngeal contractile pressures in people with OSA has been previously reported, with possible contributing mechanisms, including the low-frequency vibrations and obstructive episodes associated with OSA.[31]

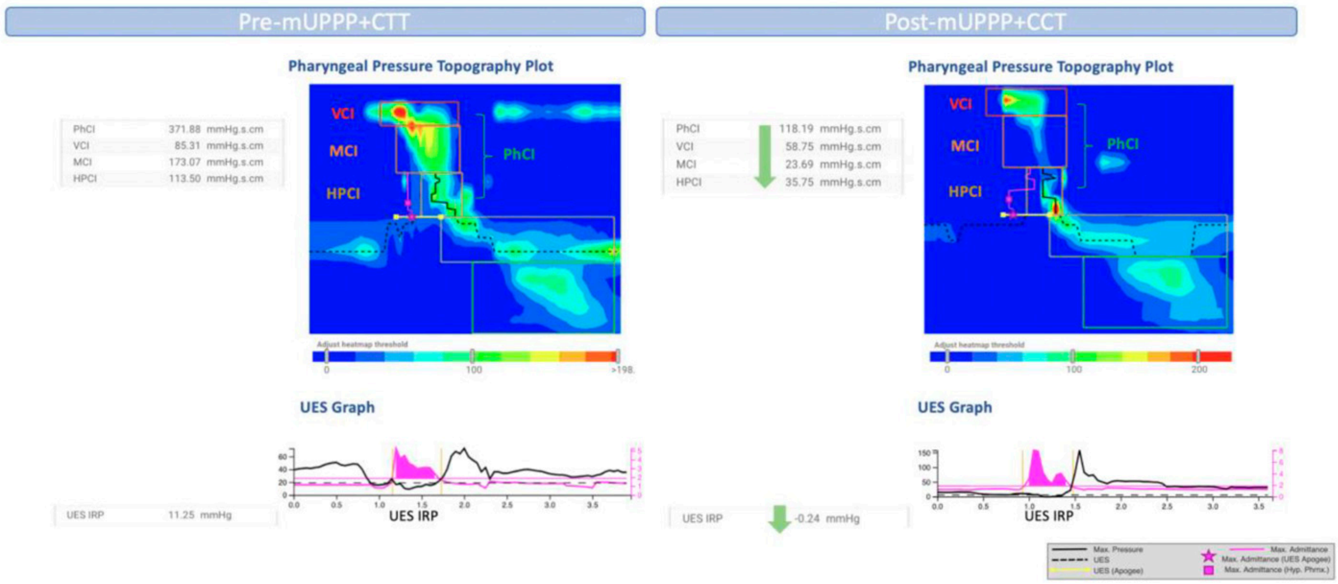
Effects on mesopharyngeal and hypopharyngeal pressures

The tongue base plays a vital role during swallowing by generating the driving pressures behind the bolus,[39,40] which, in concert with hypopharyngeal pressure profiles, results in efficient bolus clearance during swallowing.[39] Therefore, it is plausible that the reduced mesopharyngeal and hypopharyngeal contractile pressures are a result of the CCT component of the surgery, which is hypothesized to stiffen the tongue base.[41] Of note, although reduced, the observed mesopharyngeal and hypopharyngeal contractile pressures remained within normative ranges.[28] This may reflect the recent findings that following CCT, tongue base volume did not significantly reduce, although the position appeared to move superiorly.[42]

Effects on UES relaxation pressures

Consistent with our previous study exploring swallow biomechanics in OSA,[31] increased UES relaxation pressures were present in this cohort presurgery. Furthermore, a significant reduction of UES relaxation pressures was observed

Figure 2—Comparison of a single swallow of 10 mL volume thin liquid pre- and post-mUPPP+CCT.



The high-resolution pharyngeal pressure topography plot with accompanying PhCI, VCI, MCI, and HPCI mm Hg s cm values are shown. A reduction of the PhCI along with the subcomponents (velo-, meso- and hypo-pharyngeal contractile integrals following surgery are seen and represented with a green arrow. The UES graph shows a reduction in UES IRP following the surgery. mUPPP+CCT = modified uvulopalatopharyngoplasty and coblation channeling of the tongue, PhCI = pharyngeal contractile integral, UES IRP = upper esophageal sphincter, UES IRP = UES relaxation pressure, VCI = velopharyngeal contractility

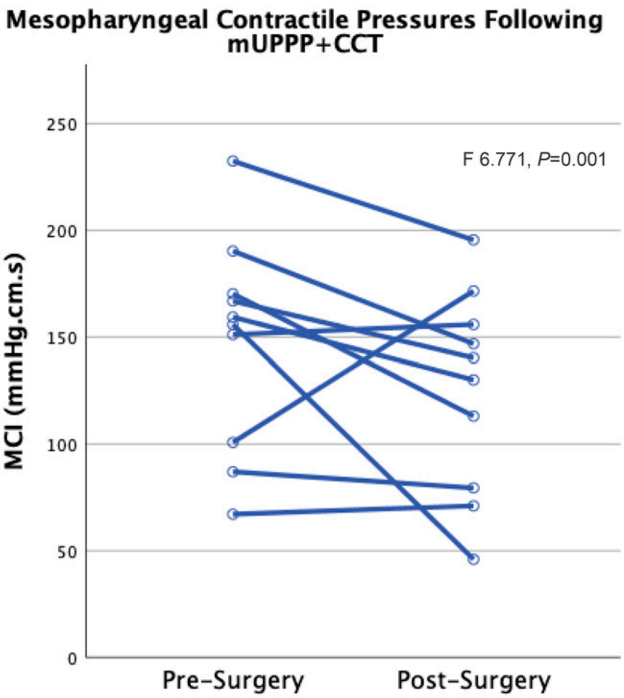
following mUPPP+CCT, approaching normative ranges.[28] This is suggestive of a reduced degree of UES restriction during swallowing[43] that may result from reduced meso-pharyngeal contractile pressures.

Effects on the overall pharyngeal swallowing mechanism

The pharyngeal contractile pressures and bolus movement during swallowing, measured by an indwelling HRPM catheter, are affected by a range of factors. These include the structure of the swallowing muscles and pharyngeal luminal size, which may be impacted by mUPPP+CCT surgery. Swallowing is a pressure-driven process in which, at the onset of the swallow, velopharyngeal contraction seals the pharyngeal chamber proximally. Mesopharyngeal pressure generation via tongue base retraction 1) generates intraluminal bolus distension forces in the hypopharynx and at the UES, resulting in a favorable pressure gradient for bolus flow[40,44]; and 2) occludes the lumen, clearing the bolus and generating an isometric mesopharyngeal pressure wave.[45] Thus, the combined findings of reduced UES relaxation and mesopharyngeal contractile pressures may represent impaired force-generating capacity at the level of the mesopharynx, which is the primary target of the CCT. The reduction in mesopharyngeal pressures may reflect alterations in tissue tension reducing collapsibility of the tongue base, rather than reduced tongue base volume.[42] It is important to recognize that mesopharyngeal pressures below the normal limits may diminish the driving pressures behind the bolus during swallowing, reducing bolus propulsion. A standardized approach for CCT[14] is recommended to minimize potential of mesopharyngeal insufficiency. In contrast to previous suggestions,[36] the small degree of velar soft tissue resection in the mUPPP technique[42] did not appear to have any measurable impact on swallowing and is reflective of the reconstructive surgical approach. The contemporary nature of this procedure produces subtle changes in swallowing biomechanics but does not adversely impact swallowing in a clinically meaningful manner.

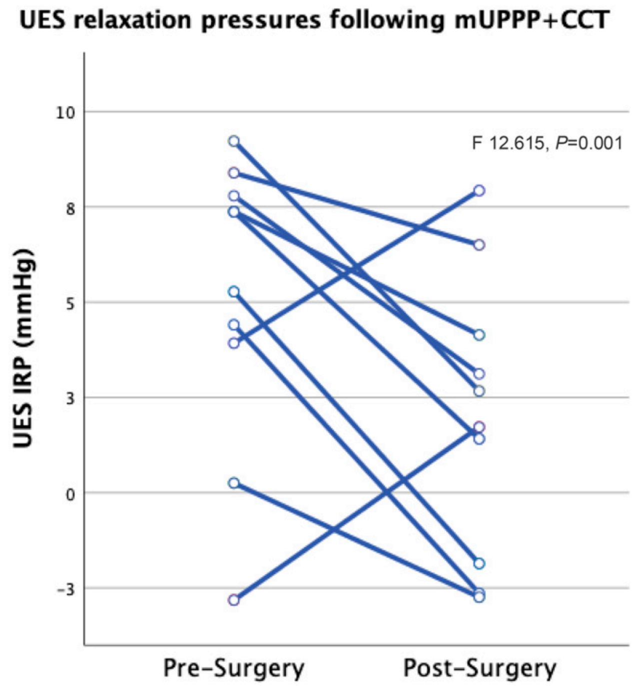
Taken together with the unchanged patient-reported swallowing complaints reported here, the novel biomechanical findings may serve to reduce concerns regarding postoperative dysphagia as a complication associated with mUPPP+CCT. They support VFSS-based studies, which have reported minimal effects of airway surgery for OSA on swallowing function,[23,24] suggesting that the mUPPP+CCT technique may not principally be associated with impaired swallowing function but may instead emphasize pre-existing swallowing alterations in people with OSA.[23,24] The mechanistic information garnered from this study raises future considerations, including 1) whether there is a role for preoperative manometry to identify those patients with OSA with pre-existing mesopharyngeal insufficiency whereby CCT may exacerbate onset of dysphagia symptoms; and 2) whether patients undergoing mUPPP+CCT will be more at risk of experiencing aging-related disordered swallowing. These findings highlight the application of the HRPM technology and could be utilized for evaluating swallowing outcomes of other surgical procedures for management of OSA.

Figure 3—Reduction of tongue base contractile pressure integrals following mUPPP+CCT surgery (n = 10).



Individual participants swallowing 10 mL thin fluids presurgery and postsurgery mesopharyngeal contractile integral values are shown. Six show a reduction and 1 shows an increase of mesopharyngeal contractile pressures following surgery. Three appear consistent between the 2 time points. MCI = mesopharyngeal contractile integral, mUPPP+CCT = modified uvulatopharyngoplasty and coblation channeling of the tongue

Figure 4—Reduction of UES relaxation pressure following mUPPP+CCT (n = 10).



Individual participants swallowing 10 mL thin fluids presurgery and postsurgery UES relaxation pressure are shown. Eight participants show a reduction and 2 show an increase of UES relaxation pressures following surgery. mUPPP+CCT = modified uvulatopharyngoplasty and coblation channeling of the tongue, UES IRP = upper esophageal sphincter integrated relaxation pressure.

The following limitations of this study are acknowledged: 1) the number of participants involved in the presurgical and postsurgical analysis was relatively small (n = 10). Although it was sufficient to detect subtle changes to swallow function, a future investigation of a larger sample with a longer time frame is needed to confirm these findings with respect to symptom outcomes. 2) Although reflux symptoms were part of the exclusion criteria, a validated patient-reported outcome measure was not included. This may be a consideration in future studies as laryngopharyngeal reflux has been shown as an independent risk factor of dysphagia following upper airway surgery for OSA.[46] 3) This current study did not correlate the HRPM findings with visual instrumental swallowing assessments, such as VFSS. The inclusion may support future clinical translation of the HRPM findings. 4) This study assessed swallowing outcomes of a specific surgical technique, and the findings may not be generalizable to other surgical approaches.

CONCLUSIONS

This HRPM study provides fundamental insights of the biomechanical pharyngeal swallowing outcomes following mUPPP+CCT surgery in a moderate-severe OSA cohort. Biomechanical alterations to the swallowing mechanism following mUPPP+CCT were identified at distinct anatomical locations. However, perceived dysphagia symptoms were unchanged following surgery, suggesting these alterations were insufficient to worsen patient-reported swallowing. Further studies in larger cohorts are required to verify these novel findings.

ABBREVIATIONS

AHI, apnea-hypopnea index
BMI, body mass index
HCI, hypopharyngeal contractile integral
HRPM, high-resolution pharyngeal manometry
IDDSI, International Dysphagia Diet Standardization Initiative
mUPPP+CCT, modified uvulopalatopharyngoplasty and coblation channeling of the tongue
OSA, obstructive sleep apnea
SSQ, Sydney Swallow Questionnaire
UES, upper esophageal sphincter
UES IRP, upper esophageal sphincter integrated relaxation pressure
VFSS, videofluoroscopic swallow study

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