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ORIGINAL RESEARCH

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Persistence of lower vocal intensity in vocal fold paralysis with cricothyroid impairment after hyaluronate injection

Kuo-Cheng Liu MD[1,2,3] | Yi-An Lu MD[4] | Hsiu-Feng Chuang BS[4] | Li-Jen Hsin MD[4,5] | Wan-Ni Lin MD[4,5] | Alice M. K. Wong MD[2] | Yu-Cheng Pei MD, PhD[2,3,5,6] | Tuan-Jen Fang MD, FICS[4,5]

[1]Department of Physical Medicine and Rehabilitation, New Taipei Municipal TuCheng Hospital (Built and Operated by Chang Gung Medical Foundation), New Taipei City, Taiwan

[2]Department of Physical Medicine and Rehabilitation, Chang Gung Memorial Hospital at Linkou, Taoyuan, Taiwan

[3]Graduate School of Science Design Program in Innovation for Smart Medicine, Chang Gung University, Taoyuan, Taiwan

[4]Department of Otolaryngology, Chang Gung Memorial Hospital at Linkou, Taoyuan, Taiwan

[5]School of Medicine, Chang Gung University, Taoyuan, Taiwan

[6]Center of Vascularized Tissue Allograft, Chang Gung Memorial Hospital at Linkou, Taoyuan, Taiwan

Correspondence
Tuan-Jen Fang, Department of Otolaryngology, Chang Gung Memorial Hospital at Linkou, 5 Fushing Street, Taoyuan 333, Taiwan.
Email: fang3109@adm.cgmh.org.tw

Yu-Cheng Pei, Department of Physical Medicine and Rehabilitation, Chang Gung Memorial Hospital at Linkou, 5 Fushing Street, Taoyuan 333, Taiwan.
Email: yspeii@gmail.com

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Abstract

Background: Unilateral vocal fold paralysis (UVFP) affects the glottal gap, voice, and aerodynamics, whereas injection laryngoplasty (IL) using hyaluronate is an effective treatment for UVFP by decreasing the glottal gap to improve voice. Previous studies have shown that the involvement of cricothyroid (CT) muscle in UVFP patients further affects patients' aerodynamics, but it remains unclear whether the difference remains after IL. This study investigates whether the aerodynamic features observed in UVFP with CT involvement could still be observed after IL.

Methods: This study recruited UVFP patients with dysphonia, and IL was performed within 6 months of initial symptoms. All subjects received assessments including videolaryngoscopy, voice analysis, and aerodynamics at three time points: before IL, 1 month after IL, and 6 months after IL. The glottal gap, voice, and aerodynamics between patients with and without CT involvement (the CT+ and CT− groups) were compared, and the change (Δ) before and after IL and repeated-measures analysis of variance (ANOVA) were also compared between the two groups.

Result: A total of 71 patients with UVFP (22 in the CT+ group and 49 in the CT− group) were analyzed. After IL, the CT+ group showed a lower sound pressure level (SPL), higher Δair pressure, and smaller Δaerodynamic power than the CT− group.

Conclusion: The CT+ group had a lower SPL, even after elevating air pressure to attempt to achieve a higher vocal intensity. The results suggest that although closure of the glottal gap was achieved by IL, the CT+ group still had a lower loudness and needed to sustain a higher peak air pressure when producing voice.

Level of evidence: Level 4.

KEYWORDS
aerodynamics, air pressure, cricothyroid, injection laryngoplasty, unilateral vocal fold paralysis

1 | INTRODUCTION

Unilateral vocal fold paralysis (UVFP) is manifested with dysphonia that resulted from surgical injury, trauma, malignancy, or idiopathic reason.[1,2] The specific pathological vocal patterns, such as limited loudness, speaking with effort, easy voice fatigue, and breathy voice,[3,4] further affect the patient's quality of life.[5] Factors such as glottal closure[6] or vocal fold (VF) tension[7,8] could also affect voice quality among UVFP patients. The ability to maintain a small glottal gap facilitates the buildup of subglottal pressure and further lowers phonation threshold pressure.[9,10] The increase in peak air pressure and expiratory airflow during voicing in UVFP patients indicates that more expiratory effort is needed as a result of a lack of laryngeal control and wider glottal gap.[11–13] In addition to glottal closure, Zhang et al. found that the tightening mechanism of the VF during phonation is crucial for maintaining adductory position.[8] A decrease in VF tension makes the VFs unable to resist outward airflow and could thus be blown apart during phonation. Thus, the subglottal pressure cannot be elevated when producing voices with a higher intensity. Therefore, VF tension controlled by the cricothyroid (CT) muscle is also an important factor that determines voice quality.

The impact of CT muscle impairment in UVFP patients has been an important research issue, as it can be used for patient stratification and could yield knowledge regarding the functional role of CT muscle during voice production. Indeed, it was found that although CT muscle dysfunction does not affect VF position,[14,15] it could limit the magnitude of VF vibration.[16] From our recent reports, UVFP patients with CT muscle involvement (patients with denervation in both thyroarytenoid-lateral cricoarytenoid [TA-LCA] muscle complex and CT muscle) had a poorer long-term prognosis than those without CT muscle involvement (those with denervation only in the TA-LCA muscle complex).[17] In several animal studies, collateral reinnervation from superior laryngeal nerve facilitates reinnervation after recurrent laryngeal nerve injury.[18,19] We suggest that Galen's anastomosis, which communicates the recurrent laryngeal nerve and superior laryngeal nerve, might mediate reinnervation to the TA-LCA muscle complex after recurrent laryngeal nerve injury.[17] Regarding the effect of CT involvement on aerodynamics during voicing, we also noted that CT impairment further reduces sound pressure level (SPL), peak air pressure, and aerodynamic power in UVFP,[11] indicating that activities in the CT muscle affect aerodynamic performance in UVFP patients, although it does not influence VF position. These findings reveal that there are different mechanisms and aerodynamic patterns between UVFP patients with and without CT muscle involvement.

Injection laryngoplasty (IL) using hyaluronate is an effective temporal treatment for patients with UVFP and is becoming more popular.[20] IL could improve voice quality by augmenting the paralyzed cord and thus reduce the need for permanent laryngoplasty.[21,22] However, in cases with concomitant CT involvement, there were different presentations to those with isolated recurrent laryngeal nerve injuries. The impact of CT involvement on voice production after IL has not yet been reported. To tackle this question, in the present study, we compared the temporal changes in aerodynamics between UVFP patients receiving IL with and without CT involvement. We hypothesized that UVFP with CT involvement could affect the patient's aerodynamics even after IL, a property that could shed light on the pathophysiological roles of CT muscle in dysphonia.

2 | MATERIALS AND METHODS

2.1 | Patients

Patients with UVFP presenting dysphonia were recruited from single medical center and all data was collected from October 2015 to February 2019. Written informed consent was obtained from each subject prior to recruitment. The diagnosis of UVFP was confirmed by both limited movement of the VF observed in videolaryngoscopy and denervation changes of the TA-LCA muscle complex observed in laryngeal electromyography (LEMG). All subjects were divided into two groups based on the LEMG results: UVFP with CT muscle involvement (CT+ group) and without CT muscle involvement (CT− group).

IL using hyaluronate was conducted within 6 months of their initial symptoms. Assessments including videolaryngoscopy, acoustic voice analysis, and aerodynamics were applied to all participants at three time points: before IL (Pre-IL), 1 month after IL (Post-IL 1 M), and 6 months after IL (Post-IL 6 M). Patients with a former history of VF palsy, intolerability to all assessments, normal electrodiagnostic findings in the TA-LCA muscles, or inability to complete the post-IL 6 M follow-up were excluded. The study was conducted following the Declaration of Helsinki and was approved by the Institutional Review Board of the Chang Gung Medical Foundation.

2.2 | Assessments

2.2.1 | LEMG

We examined LEMG on bilateral TA-LCA muscle complexes and CT muscles, and the procedures were as described previously.[11] The insertional activity and spontaneous activities were observed using the concentric needle, and the motor unit and recruitment analyses were recorded. Abnormal LEMG findings were defined as denervation changes that can be represented by pathological spontaneous activities (such as positive sharp waves, fibrillation, and complex repetitive discharge), >30% polyphasic waves, and reduced interference patterns.

2.2.2 | Videolaryngoscopy

The glottal gap and the movement of glottis were observed using videolaryngoscopy. All subjects were asked to vocalize /i/ with modal pitch and regular loudness during assessment. The images of vocal slits were recorded throughout several phonatory cycles, from which, based on the method developed by Omori et al.,[23] the closed and open phase normalized glottal gap area (NGGA) were analyzed using image processing computer software (ImageJ 1.44p, National Institutes of Health, Bethesda, MD, USA).

2.2.3 | Acoustic voice analysis

We recorded parameters including the maximum phonation time, SZ ratio, fundamental frequency, jitter, shimmer, and harmonic-to-noise ratio. First, all subjects were asked to sustain /a/ sound. The maximum phonation time is the longest phonatory duration when producing the /a/ sound and is considered as an indirect estimation of the airflow rate.[24,25] Second, each subject was asked to vocalize an /s/ sound and then a /z/ sound. The ratio of the duration of an /s/ sound to a /z/ sound is the SZ ratio, which reflects the ability to control vocal cord. The perturbations of voice frequency and amplitude were recorded as jitter and shimmer respectively, which are regarded as indicators of voice stability.[26] Finally, the periodic and nonperiodic components of a voice were observed and the ratio between them is defined as the harmonic-to-noise ratio, which is used to measure the quantity of noise in the voice.[26]

2.2.4 | Aerodynamic analysis

The procedures of voice aerodynamic studies were described previously.[11] All subjects were asked to receive three trials for each protocol, and all parameters were recorded and averaged from the three trials. The parameters included maximal and mean phonatory SPL, peak and mean peak air pressure, peak and mean airflow during voicing, aerodynamic power, resistance, and efficiency. The primary outcome of this study is SPL, air pressure, and aerodynamic power.

The SPLs are defined as the loudness of voice and are measured from syllable train with the vowel /a/. The peak air pressure is the measured peak intraoral air pressure when producing the plosive consonant /p/ and is regarded as an analog to the subglottal pressure.[27] The airflow during voicing is defined as the expiratory air volume divided by the duration of phonatory /a/ segments. Aforementioned measured values are further used to calculate aerodynamic power, resistance, and efficiency to evaluate aerodynamic performance (KayPENTAX Corp, 2010).

2.3 | IL using hyaluronate

Prior to injection, anesthesia of the nasal mucosa was conducted, followed by transnasal insertion of a distal-chip laryngoscope (Laryngoscope: ENF Type V2; Platform: EVIS Exera II; Olympus Optical Co, Ltd, Tokyo, Japan). After visualization of the glottis, a 23- or 25-gauge needle was inserted through the CT membrane into the VF, and 0.5 mL of 2% lidocaine was pushed into the laryngo trachea for anesthesia. Transcricothyroid membrane injection of hyaluronate was then performed under monitoring by flexible laryngoscopy. Finally, the subject was asked to project their voice at the end of the injection to confirm VF position and voice satisfaction.

2.4 | Statistical analysis

The SPSS (SPSS Inc., Chicago, IL, USA) was used for data analysis and the data are presented as the mean ± standard deviation or number

TABLE 1 Comparison of the demographics between the CT+ and CT− groups

Parameter	Total N = 71	CT+ group N = 22	CT− group N = 49	*p* value
Age (year)	52.6 ± 12.4	49.2 ± 13.4	54.1 ± 11.7	.124
Sex (male/female)	47/24	11/11	36/13	.053
Paralysis side (left/right)	48/23	11/11	37/12	.034*
Time post paralysis (month)	2. 9 ± 1.7	3.8 ± 1.8	2.5 ± 1.5	.003**
Pathogenesis (*n*, %)				
Esophageal	12	0	12	
Mediastinum surgery	5	0	5	
Heart surgery	4	0	4	
Lung surgery	7	0	7	
Thyroidectomy[a]	25	12	13	
Idiopathic	9	3	6	
Skull base or brain surgery	4	4	0	
Cervical spine surgery	4	2	2	
Thyroid tumor[b]	1	1	0	

Abbreviations: CT, cricothyroid; UVFP, unilateral vocal fold paralysis.
[a]UVFP is related to post-operative change.
[b]UVFP is related to tumor effect and not related to further surgery.
*$p < .05$. **$p < .01$.

of patients. For comparisons between the CT+ and CT− groups, the continuous variables were analyzed using Student's *t*-test, and the categorical variables were analyzed using the X^2 test. Repeated measures ANOVA with least significant difference main effect analysis was applied for pairwise comparisons between Pre-IL versus Post-IL 1 M and between Pre-IL versus Post-IL 6 M. Statistical significance was accepted at $p < .05$.

3 | RESULTS

One hundred ninety-four UVFP patients were recruited first, of whom five were excluded due to a normal TA-LCA muscle complex in LEMG, 14 were excluded because of incomplete LEMG data, and 104 were excluded due to being unable to complete the 6-month follow-up. Finally, 71 UVFP patients were analyzed, among whom 22 had CT involvement (CT+ group) and the remaining 49 did not (CT− group). The patient demographics and etiology of UVFP were listed in Table 1. There were no statistically significant differences in age ($p = .124$) or sex ($p = .053$) between the CT+ and CT− groups. However, the CT+ group showed a higher ratio of right-side paralysis ($p = .034$) and a longer time after paralysis ($p = .003$) than the CT− group.

The comparison of their videolaryngoscopy and acoustic voice analysis between the CT+ and CT− groups were listed in Table 2. At each of the assessment time points, including Pre-IL, Post-IL 1 M, and Post-IL 6 M, there were no statistically significant differences between the two groups in their closed-phase NGGA, open-phase NGGA, or parameters in acoustic voice analysis. In the repeated-measures ANOVA, patients in both groups had improved NGGA and all parameters in acoustic voice analysis (all $p < .05$), instead of fundamental frequency and shimmer in the CT+ group (Post-IL 1 M) during 6 months follow-up. The interaction effect of repeated-measures ANOVA showed that there were no differences in the improvement of NGGA and parameters in acoustic voice analysis between the two groups.

Table 3 shows the comparison of aerodynamic parameters between the CT+ and CT− groups. Prior to IL, the CT+ group showed lower maximal SPL ($p = .023$), mean SPL ($p = .024$), peak air pressure ($p < .001$), mean peak air pressure ($p = .001$), and aerodynamic power ($p = .007$) values than the CT− group, indicating lower sound pressure and lower power production during voicing in the CT+ group. One month after IL, the CT+ group showed a lower value in maximal SPL ($p = .032$), mean SPL ($p = .026$), and aerodynamic power ($p = .009$) than the CT− group, indicating a weaker sound pressure and lower power production during voicing in the CT+ group even after IL. Although the CT+ group had a lower peak expiratory airflow ($p = .005$) and mean airflow during voicing ($p = .021$) than the CT− group (Table 3), there were no differences in the aerodynamic change in airflow between the CT+ and CT− groups (Table 4), indicating comparable improvement in expiratory airflow after IL. Six months after IL, the CT+ group still displayed a lower maximal SPL ($p = .009$) and mean SPL ($p = .022$) than the CT− group. In the repeated-measures ANOVA, patients in both groups had improved most parameters in aerodynamic (all $p < .05$), but the improvement was

TABLE 2 The comparison of videolaryngoscopy and acoustic voice analysis between the CT+ and CT− groups at Pre-IL, Post-IL 1 M, and Post-IL 6 M

Parameter	Pre-IL Group CT+ (N = 22)	Pre-IL Group CT− (N = 49)	Pre-IL p value	Post-IL 1 M Group CT+ (N = 22)	Post-IL 1 M Group CT− (N = 49)	Post-IL 1 M p value	Post-IL 6 M Group CT+ (N = 22)	Post-IL 6 M Group CT− (N = 49)	Post-IL 6 M p value	Time × group interaction p value
Videolaryngoscopy										
Close-phase NGGA	9.37 ± 7.04	10.62 ± 10.64	.619	0.94 ± 1.44†††	1.25 ± 2.35†††	.571	1.41 ± 2.42†††	1.59 ± 2.57†††	.774	.786
Open-phase NGGA	16.57 ± 7.48	17.04 ± 12.44	.871	7.66 ± 3.56†††	8.70 ± 5.01†††	.396	8.56 ± 4.54†††	10.91 ± 7.56††	.182	.558
Acoustic voice analysis										
Maximum phonation time (s)	5.17 ± 3.40	4.62 ± 3.83	.479	9.86 ± 4.28†††	10.35 ± 4.78†††	.682	10.30 ± 5.78††	12.30 ± 6.66†††	.244	.134
SZ ratio	2.19 ± 0.91	2.16 ± 1.18	.921	1.32 ± 0.50†††	1.21 ± 0.56†††	.406	1.22 ± 0.45†††	1.18 ± 0.77†††	.825	.918
Fundamental frequency (Hz)	185.4 ± 58.8	172.9 ± 58.6	.409	168.6 ± 38.4	160.0 ± 57.1†	.525	161.3 ± 38.4†	154.0 ± 45.2††	.528	.840
Jitter (%)	4.95 ± 3.26	5.26 ± 3.90	.749	2.04 ± 1.11†††	2.06 ± 1.71†††	.952	1.96 ± 0.83††	1.57 ± 1.03†††	.132	.656
Shimmer (dB)	0.92 ± 0.84	0.95 ± 0.69	.857	0.56 ± 0.73	0.38 ± 0.26†††	.273	0.37 ± 0.19††	0.31 ± 0.18†††	.255	.642
Harmonic-to-noise ratio	6.15 ± 2.73	6.26 ± 3.47	.891	8.90 ± 3.13††	8.34 ± 2.11†††	.379	8.43 ± 2.09††	8.23 ± 1.96††	.708	.638

Abbreviations: CT, cricothyroid; IL: injection laryngoplasty; NGGA: normalized glottal gap area; Post-IL 1 M: 1 months after IL; Post-IL 6 M: 6 months after IL; Pre-IL: before IL.

$^{\dagger}p < .05$, compared with Pre-IL.

$^{\dagger\dagger}p < 0.01$, compared with Pre-IL.

$^{\dagger\dagger\dagger}p < 0.001$, compared with Pre-IL.

TABLE 3 The comparison of aerodynamics between the CT+ and CT− groups at Pre-IL, Post-IL 1 M, and Post-IL 6 M

	Pre-IL			Post-IL 1 M			Post-IL 6 M			
	Group			Group			Group			
Parameter	CT+ ($N = 22$)	CT− ($N = 49$)	*p* value	CT+ ($N = 22$)	CT− ($N = 49$)	*p* value	CT+ ($N = 22$)	CT− ($N = 49$)	*p* value	Time × group interaction *p* value
Maximal SPL (dB)	76.42 ± 5.11	79.60 ± 5.42	.023*	78.48 ± 4.58†	81.20 ± 4.95	.032*	79.32 ± 5.60†	83.10 ± 5.45†††	.009**	.682
Mean SPL during voicing (dB)	71.49 ± 4.28	74.45 ± 5.28	.024*	73.81 ± 4.95†	76.64 ± 4.79††	.026*	74.73 ± 5.36††	78.11 ± 5.75†††	.022*	.892
Peak air pressure (cm H_2O)	9.63 ± 2.53	13.10 ± 5.29	<.001***	9.64 ± 2.32	10.85 ± 3.67††	.159	11.04 ± 3.21††	11.86 ± 4.23	.423	.016*
Mean peak air pressure (cm H_2O)	7.06 ± 1.92	9.45 ± 3.73	.001**	7.34 ± 1.94	8.03 ± 2.61††	.274	8.18 ± 2.23††	8.94 ± 3.20	.317	.032*
Peak expiratory airflow (L/s)	0.81 ± 0.42	1.07 ± 0.56	.062	0.39 ± 0.13†††	0.57 ± 0.39†††	.005**	0.51 ± 0.29†††	0.63 ± 0.54†††	.210	.475
Expiratory volume (L)	0.75 ± 0.49	0.82 ± 0.52	.595	0.39 ± 0.22†††	0.53 ± 0.40††	.124	0.50 ± 0.45††	0.57 ± 0.49††	.570	.792
Mean airflow during voicing (L/s)	0.52 ± 0.31	0.66 ± 0.41	.117	0.20 ± 0.08†††	0.29 ± 0.25†††	.021*	0.26 ± 0.18†††	0.31 ± 0.30†††	.396	.450
Aerodynamic power (W)	0.40 ± 0.33	0.70 ± 0.57	.007**	0.15 ± 0.07††	0.25 ± 0.24†††	.009**	0.21 ± 0.12††	0.33 ± 0.44†††	.075	.135
Aerodynamic resistance (cm H_2O/(L/s))	19.65 ± 19.92	22.40 ± 27.88	.678	49.68 ± 44.38††	53.54 ± 59.65†††	.787	60.25 ± 94.76†	66.50 ± 86.70††	.787	.901
Aerodynamic efficiency (ppm)	10.70 ± 11.34	20.22 ± 31.27	.065	67.12 ± 118.61†	78.86 ± 93.38†††	.654	69.93 ± 103.63††	107.23 ± 143.79††	.279	.552

Abbreviations: CT, cricothyroid; IL, injection laryngoplasty; Post-IL 1 M: 1 months after IL; Post-IL 6 M: 6 months after IL; Pre-IL: before IL; SPL: sound pressure level.

*p < .05. **p < .01. ***p < .001. †p < .05, compared with Pre-IL using main effect analysis of repeated measures ANOVA.

††p < .01, compared with Pre-IL using main effect analysis of repeated measures ANOVA.

†††p < .001, compared with Pre-IL using main effect analysis of repeated measures ANOVA.

TABLE 4 The comparison of the changes between Pre-IL and Post-IL 1 M in videolaryngoscopy, acoustic voice analysis, and aerodynamics between the CT+ and CT− groups

Parameter	Group CT+ ($N = 22$)	Group CT− ($N = 49$)	*p* value	Cohen's *d*
Videolaryngoscopy				
Close-phase NGGA	−8.48 ± 7.14	−9.17 ± 10.49	.778	0.077
Open-phase NGGA	−9.25 ± 6.38	−8.17 ± 12.76	.635	0.107
Acoustic voice analysis				
Maximum phonation time (s)	−0.50 ± 4.85	1.95 ± 5.23	.066	0.486
SZ ratio	−0.21 ± 0.75	−0.02 ± 0.67	.296	0.267
Fundamental frequency (Hz)	−21.96 ± 60.32	−6.04 ± 40.16	.193	0.311
Jitter (%)	−0.26 ± 1.62	−0.50 ± 2.10	.633	0.128
Shimmer (dB)	−0.23 ± 0.80	−0.07 ± 0.28	.376	0.267
Harmonic-to-noise ratio	−1.24 ± 4.55	−0.11 ± 2.78	.292	0.300
Aerodynamic analysis				
Maximal SPL (dB)	2.07 ± 4.54	1.59 ± 5.71	.732	0.093
Mean SPL during voicing (dB)	2.32 ± 4.15	2.19 ± 5.57	.923	0.026
Peak air pressure (cm H_2O)	0.01 ± 2.63	−2.25 ± 4.79	.013*	0.585
Mean peak air pressure (cm H_2O)	0.28 ± 1.85	−1.43 ± 3.27	.007**	0.644
Peak expiratory airflow (L/s)	−0.42 ± 0.36	−0.49 ± 0.47	.506	0.167
Expiratory volume (L)	−0.36 ± 0.36	−0.29 ± 0.55	.522	0.151
Mean airflow during voicing (L/s)	−0.31 ± 0.27	−0.36 ± 0.35	.572	0.160
Aerodynamic power (W)	−0.25 ± 0.30	−0.45 ± 0.53	.049*	0.464
Aerodynamic resistance (cmH_2O/(L/s))	30.03 ± 47.34	31.14 ± 54.97	.935	0.022
Aerodynamic efficiency (ppm)	56.42 ± 113.21	58.64 ± 89.22	.929	0.022

Abbreviations: CT, cricothyroid; IL, injection laryngoplasty; NGGA: normalized glottal gap area; Post-IL 1 M: 1 months after IL; Pre-IL: before IL; SPL: sound pressure level.
$^*p < .05$. $^{**}p < .01$.

not significant in peak air pressure and mean peak air pressure in the CT+ group (Post-IL 1 M), maximal SPL in the CT− group (Post-IL 1 M), and peak air pressure and mean peak air pressure in the CT− group (Post-IL 6 M). The interaction effect of repeated-measures ANOVA showed that the CT+ group had a worse improvement in peak air pressure and mean air pressure (interaction effect, $p = .016$ and .032, respectively) than the CT− group.

Table 4 shows the comparison between the CT+ and CT− groups in their changes (Δ) from pre-IL to post-IL 1 M in their videolaryngoscopy, acoustic voice analysis, and aerodynamics. The two groups did not differ in their Δclosed-phase NGGA, Δopen-phase NGGA, or changes in parameters in acoustic voice analysis (all $p > .05$). In the analysis of aerodynamics, the CT+ group had an increase in their peak air pressure ($p = .013$) and mean air pressure ($p = .007$) compared with the CT− group; furthermore, the CT+ group had a smaller reduction in aerodynamic power ($p = .049$) than the CT− group.

4 | DISCUSSION

To the best of our knowledge, this study is the first to report whether UVFP with CT involvement could affect patients' aerodynamics even after IL. It is noteworthy that elevated peak air pressure and mean peak air pressure were still noted after IL for CT+ UVFP patients. In addition, the CT+ group had a lower maximal SPL and mean SPL during voicing than the CT− group. These findings persisted for 6 months after IL, even though patients in the CT+ group showed improved SPL, expiratory airflow, aerodynamic power, resistance, and efficiency.

IL is an effective treatment for pathologic voice patterns among UVFP patients by maintaining the patient's voice and quality of life.[28–30] The glottal gap could be corrected by hyaluronate without affecting the mucosal vibration, a property that is similar to that observed in this study. In the present study, although most of the parameters were better at 1-month post-IL, the peak air pressure in the CT+ group did not improve, suggesting that the CT+ group still needs to sustain higher peak air pressure to produce voices. Six months post-IL, although improvements could still be observed compared with pre-IL, the treatment effect was partially decreased compared with that observed 1-month post-IL. In addition to the effect of IL, there might be spontaneous reinnervation that occurred at 6 months post-IL in this study, which would also lead to the improvement of the aerodynamic performance, such as SPL and voice efficiency. However, elevated air pressure, expiratory airflow, and aerodynamic power are also noted simultaneously, which might result from the degradation of hyaluronate over time.

There are many factors that may impact voice quality among UVFP patients, including wider glottal gap,[6] imbalanced VF tension,[7] and lesser VF tension.[8] Several studies have investigated the aerodynamic performance on different voice intensity.[12,31–34] As voice intensity elevates, the subglottal pressure and expiratory airflow slightly increase in normal subjects[31,33,34] but markedly increase in UVFP patients.[12] Similar results were noted in this study, as they were shown to greatly raise air pressure and airflow to overcome low resistance due to a wider glottal gap when producing voice.[35] However, due to a similar glottal gap in the CT+ and CT− groups, VF tension is suggested to be the factor that affects aerodynamics in both groups. A loss of VF tension control makes UVFP patients with concomitant CT impairment unable to resist outward airflow, thus limiting their ability to raise their air pressure during phonation.[11] After receiving IL, both groups had an increasing SPL and decreasing expiratory airflow, a finding indicating that glottal gap approximation facilitates less air leakage and easier buildup of subglottal pressure to achieve higher vocal intensity. However, the CT+ group could not achieve a high maximal SPL compared with the CT− group, even with a rise in air pressure. Thus, the producing aerodynamic power was low. This phonatory mechanism led to a lower voice efficiency, which may cause more vocal fatigue in the CT+ group. Therefore, more attention should be given to patients with CT involvement, as they persistently apply a higher peak air pressure even after IL, thus predisposing them to experience voice fatigue.

Due to a decrease of VF tension in the CT+ group, the expiratory airflow is expected to be higher than that in the CT− group. However, at 1-month post-IL, the CT+ group has a lower peak expiratory airflow and mean airflow during voicing than the CT− group. "Peak expiratory airflow" and "mean airflow during voicing" are defined as expiratory air volume divided by the duration of the expiratory phase or voiced phase, respectively. In the present study, a less expiratory air volume was observed in the CT+ group, which further induced a reduced peak expiratory airflow and mean airflow during voicing.

There were several limitations in this study. First, there was a high rate of loss to follow-up in this study. It may affect the validity in clinic research. However, most excluded patients were unwilling to receive assessments at 6 months post-IL, and a similar proportion of patients lost to follow-up among the two groups was observed, indicating that the reason for drop-out is irrelevant to UVFP itself. Second, respiratory function tests, such as vital capacity, were not measured in this study. It may influence aerodynamic performance after thoracic surgery. However, there were no patients receiving thoracic surgery in the CT+ group, whose aerodynamic performances were worse than those in the CT− group, indicating that the observed significance of aerodynamics in this study is less likely to be related to the patients' respiratory function. Third, we did not explore the vocal condition at different vocal intensities. In our previous work that used voice range profile to assess UVFP patients, vocal loudness was affected by the interaction of the recruitment activities in the TA-LCA muscle complex and the CT muscle.[36] However, in our protocol, all participants were asked to produce a /pa/ sound three times consecutively with an appropriate pace and comfortable loudness. The pitch and the loudness did not change during assessment in this study. The protocol to assess voice production in different vocal intensities might be helpful to tell the minute differences between groups. To address these issues, more sophisticated assessments should be conducted in a future study.

5 | CONCLUSION

This study is the first to reveal a distinctive post IL deviation of aerodynamics in UVFP patients with CT muscle involvement by showing a lower maximal SPL and mean SPL during voicing, even after elevating peak air pressure and mean peak air pressure to reach a higher voice intensity. The results suggest that although closure of the glottal gap is achieved by IL, patients in the CT+ group still have a lower loudness and need to sustain higher peak air pressure to produce voice. These findings further suggest that LEMG should be conducted in those who did not achieve expected outcomes after IL and early speech language pathologist referral are necessary in UVFP with CT dysfunction.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interests.

ORCID

Alice M. K. Wong https://orcid.org/0000-0003-3586-1292
Tuan-Jen Fang https://orcid.org/0000-0002-7805-3458

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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