Do Phonatory Aerodynamic and Acoustic Measures in Connected Speech Differ Between Vocally Healthy Adults and Patients Diagnosed with Muscle Tension Dysphonia?

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Summary: Objectives. One of the presumed etiologies of primary muscle tension dysphonia (MTD) is a respiratory-phonatory disruption resulting in poor phonatory airflow in speech; however, few data exist on the differences between vocally healthy adults and patients diagnosed with MTD. The goal of this study was to compare aerodynamic and acoustic measures of self-perceived vocally healthy adults with patients diagnosed with MTD.

Study Design. Retrospective, observational, matched cohort study.

Methods. Vocally healthy adults age 19−60 years were matched on age, gender, and body mass index (BMI) to patients diagnosed with MTD. Recorded samples of the first four sentences of The Rainbow Passage were analyzed for between-group differences in the following acoustic and aerodynamic dependent measures in connected speech: mean airflow during voicing, breath number, reading passage duration, inspiratory and expiratory durations, phonation time, inspiratory and expiratory volumes, cepstral peak prominence (CPP), CPP standard deviation (CPP SD), low to high ratio (L/H ratio), L/H ratio SD, CPP Fo, CPP Fo SD, cepstral spectral index of dysphonia, and dB sound pressure level (SPL).

Results. One hundred and seventy participants were studied; 85 patients diagnosed with primary MTD and 85 vocally healthy control participants. The two groups differed significantly in mean SPL, duration of the reading passage, and inspiratory and expiratory airflow duration ($P \leq 0.003$). No significant differences were observed between the groups on any other phonatory aerodynamic or acoustic measure. Mean SPL, duration of the reading passage, and inspiratory and expiratory airflow durations were lower and longer, respectively, in patients with MTD. Ranges and standard deviations were greater for all aerodynamic and acoustic measurements in patients with MTD.

Conclusion. Large variability in aerodynamic and acoustic measurements were observed in patients with primary MTD with no salient differences at the group level compared to vocally healthy participants. Individual phonatory aerodynamic and acoustic profiles should be used when setting goals for patient treatment plans and to track response to treatment for patients with MTD. Taken in its entirety, connected speech from patients diagnosed with MTD essentially reflect normal acoustic and aerodynamic values.

Key Words: Muscle tension dysphonia−MTD−Aerodynamic−Acoustic−Connected speech.

INTRODUCTION

Primary muscle tension dysphonia (MTD) is a voice disorder that presumes excess tension in the intrinsic and extrinsic muscles of the larynx as the underlying source of dysphonia in the absence of any anatomical or neurological laryngeal abnormalities.[1−7] However, in addition to abnormal tensions thought to occur in the laryngeal muscles, concurrent involvement across respiratory subsystems have also been implicated in MTD.[8−10] One of the mechanistic etiologies thought to be responsible for primary MTD is an abnormal coordinative pattern of the respiratory-phonatory system.[9−11] Stone and colleagues were the first to introduce the concept of "breath-holding" in patients with MTD, involving laryngeal or chest wall mechanisms that lead to a mechanical disadvantage that manifests as primary MTD.[12] Later, Gillespie *et al.* were the first to identify an aerodynamic profile in women diagnosed with MTD that quantitatively characterized the clinical phenomenon of "breath-holding" in a syllable-string task.[8]

Myriad voice therapy approaches are predicated on increasing phonatory airflow to counteract the presumed mechanical disadvantage created by "breath-holding" to improve voice in patients with MTD.[12−15] Many studies have shown voice therapy to be an effective treatment for MTD, comparing patient-reported outcomes pre- and post-therapy, as well as objective aerodynamic and acoustic measures.[16−20] Specifically, improvements are noted in patients who are treated with voice therapy exercises with a clear and early target of airflow release with phonation.[12,14,17,20−22] If a theoretical premise of voice therapy for patients diagnosed with MTD is to increase coordination of their respiratory-phonatory mechanisms and return to normal functioning, a gap in the literature exists on the differences in aerodynamic and acoustic characteristics between vocally healthy adults and patients with MTD.

Accepted for publication December 23, 2019.
Declaration of Interests: None.

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Journal of Voice, Vol. 35, No. 4, pp. 663.e1−663.e7
0892-1997

https://doi.org/10.1016/j.jvoice.2019.12.019

Few studies exist that evaluate the effects of voice therapy for patients with primary MTD while comparing objective values to accepted normative data. For studies that do compare to normative values, the measurements obtained are derived from recordings of repetitive syllabic strings.[23–25] However, recently, normative aerodynamic data were published for a connected speech task in which patients read a standardized reading passage.[26] Previous studies have shown that connected speech tasks are capable of capturing treatment change across a variety of voice disorders, as well as being more ecologically valid ways to capture an individual's voice problem in their speaking voice.[26–28]

The primary objective of our study was to investigate whether there is a difference in aerodynamic measures between vocally healthy participants and patients diagnosed with MTD using a connected speech task. Our primary hypothesis was that mean airflow during voicing would be lower in patients with MTD compared to vocally healthy adults. For secondary analyses, we investigated other aerodynamic and acoustic measures of connected speech and hypothesized that these measures would be abnormal in the patients with MTD compared to norms.

METHODS

Participants

The study was approved by the University of Pittsburgh Institutional Review Board (IRB# PRO13080164). The aerodynamic and acoustic samples for the vocally healthy adults came from a previously published study on adult normative data for phonatory aerodynamics in connected speech and served as stimuli to render aerodynamic and acoustic measures.[26] Inclusion criteria for the vocally healthy adults included participants who did not have a perception of voice handicap as denoted by a Voice Handicap Index-10 (VHI-10) score < 11, (two standard deviations from the VHI-10 normative mean).[29] Additionally, a voice-specialized speech language pathologist (SLP) had to perceive a nondisordered voice. The vocally healthy cohort were monolingual, English speakers with no history of a voice problem lasting longer than 2 weeks. For comparison in this study, we only included patients age ≤ 60 years old to reduce potential effects of undiagnosed vocal fold atrophy.

Next, to minimize confounding, patients diagnosed with MTD were matched on age, gender, and body mass index (BMI) to the vocally healthy cohort. BMI was a matching variable due to respiratory differences between individuals with high and low BMI.[30] Data from patients with MTD were taken and entered into the electronic medical record as part of a routine voice lab protocol. Inclusion criteria for the MTD group included patients presenting to the University of Pittsburgh Voice Center for a voice complaint and receiving a diagnosis of primary MTD after evaluation by a voice-specialized SLP and fellowship-trained laryngologist. All patients had a VHI-10 ≥ 11, indicating a self-perceived voice handicap above the normal threshold.[29] Patients were excluded if they had any secondary voice disorders or concomitant conditions known to affect voice (eg, vocal fold lesions, vocal fold paralysis or paresis, recurrent respiratory papilloma, laryngeal cancer, progressive neurological diseases, COPD, or other pulmonary conditions).

Matching

The matching process used a variable distribution matching algorithm. Patients and controls were matched exactly on gender, and Mahalanobis distance matching was performed in an optimal 1:1 ratio to minimize differences in continuous age and BMI within pairs.[31] Based on the size of the original normative cohort, a potential 100 matches were possible, with 100 patients in the original cohort meeting inclusion criteria for comparison in this study. We defined prespecified match quality criteria in which age differences between patients and controls must have been ≤3 years, with BMI differences of no more than 3 kg/m^2 within pairs. We planned to exclude matches in which these criteria were not met.

Procedures

All voice recordings obtained from the vocally healthy and MTD cohorts were recorded using the PENTAX Phonatory Aerodynamic System 6600 (PAS 6600; PENTAX, Montvale, NJ) and analyses used the same customized protocol as described by Lewandowski et al and Gartner-Schmidt et al.[26,32] The PAS 6600 is a low-pass filtered system with nominal cutoff 10,025 Hz and sampling rate of 22,050 samples/s. The study cohort data were gathered as part of routine clinical examinations; however, all acoustic and aerodynamic files were reanalyzed by the first author (MAB) for the current investigation to ensure data quality. All participants read the first four sentences of a standardized reading passage ("The Rainbow Passage"[33]) in comfortable pitch and loudness, and results were deidentified and saved. Voice samples for the study cohort (ie, patients with MTD) used the same stimuli and were collected during the patient's initial visit to University of Pittsburgh Voice Center, as part of routine clinical care.

Aerodynamic measures

The following phonatory aerodynamic variables were analyzed: mean airflow during voicing (mL/s), number of breaths taken, inspiratory and expiratory airflow durations (s), inspiratory and expiratory volumes (L), phonation time (s), and duration of the reading passage (s) (Table 1). The acoustic measure of Sound Pressure Level in decibels (SPL) was also measured from the four sentences of The Rainbow Passage. Duration of reading passage was calculated by manually selecting thresholds for the passage from the SPL tracing depicting phonation of the first word in the phrase to the end of phonation for the last word in the phrase. Number of breaths were counted manually, only including those within these thresholds. The remaining measurements were calculated via the PAS software. Figure 1 shows a sample screenshot from the recording analysis process.

TABLE 1.
Description of Aerodynamic and Acoustic Measurements in Connected Speech

Measurement	Unit	Description
Aerodynamics		
Mean airflow during voicing	Milliliters per second	Total volume of expiratory airflow used while voicing (determined via pitch tracing) divided by the total time when voicing happened
Number of breaths taken	Ordinal	Breaths demarcated by negative airflow tracing
Inspiratory airflow duration	Seconds	Total time of inhalation (negative airflow time)
Expiratory airflow duration	Seconds	Total time of exhalation (positive airflow time)
Duration	Seconds	Total time to read passage
Phonation time	Seconds	Total time spent phonating during the recording
Inspiratory volume	Liters	Volume of inspiratory air measured across transducer
Expiratory volume	Liters	Volume of expiratory air measured across transducer
Acoustics		
Cepstral peak prominence (CPP), SD		Relative amplitude of the cepstral peak and its standard deviation
Low to high ratio (L/H ratio), SD		The ratio of low (< 4000 Hz) vs. high (> 4000 Hz) frequency spectral energy and its standard deviation
CPP Fo, SD		The fundamental frequency of the CPP and its standard deviation
Cepstral spectral index of dysphonia (CSID)		A multivariate estimate of dysphonia severity
Sound pressure level (SPL)	Decibels	Acoustic measure of loudness

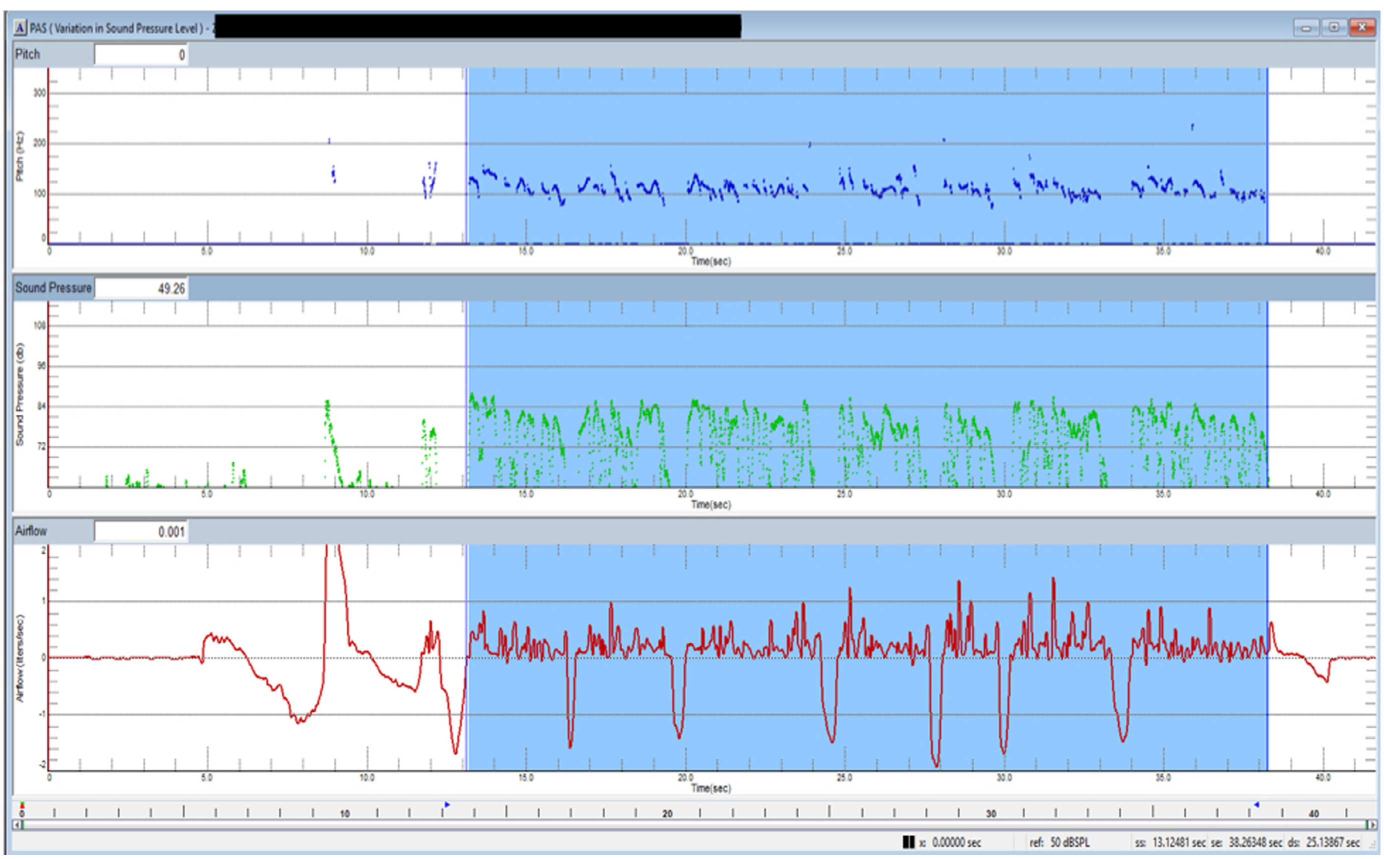

FIGURE 1. A sample PAS tracing for data analysis. Duration of reading passage was calculated by manually selecting thresholds for the passage from the dB SPL tracing depicting phonation of the first word in the phrase to the end of phonation for the last word in the phrase. Number of breaths were counted manually, only including those within these thresholds.

Acoustic measures

The following acoustic variables, from the first four sentences of The Rainbow Passage, were analyzed using the Computerized Speech Lab and Advanced Dysphonia Speech and Voice (PENTAX, Montvale, NJ) software: cepstral peak prominence (CPP), CPP SD, low to high ratio (L/H Ratio), L/H Ratio SD, CPP Fo, CPP Fo SD, Cepstral Spectral Index of Dysphonia.

Reliability of measurements

To assess accuracy of the measurements, a voice-specialized SLP from the University of Pittsburgh Voice Center also analyzed voice recordings. Twenty percent of the recordings were checked. Two-way random effects intraclass correlation coefficients (ICC) were calculated to assess interrater reliability for the variables "number of breaths" and "duration," and we found ICC = 0.993 and ICC = 0.995, respectively, indicating excellent reliability. Since all other variables (aerodynamic and acoustic) are calculated by software algorithmically after selecting the duration manually, no other statistics were calculated to assess interrater reliability.

Statistical analyses

Descriptive statistics were calculated to characterize demographic, aerodynamic, and acoustic measures for both groups after the matching process. Central tendency and dispersion of distributions were quantified using means and standard deviations for symmetric distributions and medians and interquartile ranges for skewed distributions. Both parametric and nonparametric statistical tests were chosen and used based on examination of the distributions for each variable. Departures from normality were identified visually by inspecting histograms and boxplots, as well as by performing Shapiro-Wilk tests for formal assessment.

To test for significant differences in measures between groups, two-sample Student's t tests were used for approximately normally distributed variables, and Mann-Whitney U tests were employed for variables with skewed distributions. All tests were two-sided, and an overall significance level of 0.05 was assumed. A Bonferroni correction was made to preserve the familywise error rate, accounting for multiple and potentially correlated outcomes. As a total of 16 variables were investigated, the adjusted significance level for each individual test was set at $\alpha = 0.05/16 = 0.003125$.

RESULTS

Patient characteristics

One hundred and seventy participants were studied; 85 patients diagnosed with primary MTD and 85 healthy control participants. The matching process was successful in producing similar groups based on age, gender, and BMI (Table 2). This produced 85 pairs in which patient and control ages were within 3 years of each other, and BMIs differed by no more than 3 kg/m^2 within pairs.

TABLE 2.
Demographics

	Patients with MTD (n = 85)	Control Participants (n = 85)
Age (years)	40.0 (12.7)	40.0 (13.0)
BMI (kg/m^2)	26.5 (5.3)	26.5 (5.1)
Sex		
Female	46 (54%)	46 (54%)
Male	39 (46%)	39 (46%)
VHI-10 score	0.91 (2.31)	19.42 (6.76)

All continuous and ordinal data reported as mean (SD). All categorical data reported as count (%).

The two groups matched exactly in terms of gender distribution, mean age, and mean BMI. The mean VHI-10 score of the healthy control participants was much lower than that of the participants with MTD (0.91 vs. 19.42, P value < 0.001).

Aerodynamic characteristics

Table 3 contains aerodynamic measurements from the two groups. There were no statistically significant differences in mean airflow during voicing, number of breaths taken, phonation time, expiratory volume, or inspiratory volume between the two groups. However, the MTD group had a statistically significant longer inspiratory airflow duration (4.11 vs. 3.41) and expiratory airflow duration (20.12 vs. 18.25) compared to healthy controls in both measures. The MTD group had a statistically significant longer reading time duration than the healthy control participants (24.33 s vs. 21.74 s). Mean airflow during voicing, expiratory volume, and inspiratory volumes were all larger, on average, for the group of patients with MTD compared to vocally healthy control participants, but differences were not statistically significant.

Acoustic measures

The group of patients with MTD spoke at a statistically significant lower intensity compared to healthy control participants (66.95 dB SPL vs. 68.37 dB SPL). None of the between-group differences in cepstral acoustic measures were significant (Table 4).

DISCUSSION

This study is the first to investigate differences in phonatory aerodynamics and acoustics in connected speech between patients diagnosed with MTD and age, gender, and BMI-matched vocally healthy participants. The two study cohorts differed significantly only in mean vocal intensity, duration of reading time of the standardized reading passage, and inspiratory and expiratory airflow durations. There were no significant differences in mean phonatory airflow, number of breaths taken, phonation time, inspiratory

TABLE 3.
Aerodynamic Measures

	Patients with MTD	Vocally Healthy Participants	*P* value
Mean airflow during voicing (mL/s)	155 (69)	140 (48)	0.1601†
Number of breaths	5.06 (2.36)	4.28 (1.40)	0.0419†
Inspiratory volume (L)	2.49 (1.12)	2.04 (0.76)	0.0135†
Expiratory volume (L)	3.22 (1.37)	2.75 (0.94)	0.0111*
Phonation time (seconds)	11.52 (2.64)	11.30 (2.21)	0.5639*
Duration	24.33 (4.04)	21.74 (2.82)	**<0.0001**†
Inspiratory airflow duration (s)	4.11 (1.57)	3.41 (1.02)	**<0.0009**†
Expiratory airflow duration (s)	20.12 (3.01)	18.25 (2.17)	**<0.0001***

† *P* value obtained from a two-sided Mann-Whitney U test for skewed variable distributions.
* *P* value obtained from a two-sided Student's t-test for approximately normally distributed variables.
Comparison of aerodynamic measures between patients with MTD and vocally healthy control participants. All data reported as mean (SD). *P* values highlighted in bold refer to comparisons deemed significant at the Bonferroni-corrected significance level of $\alpha = 0.05/16 = 0.003125$.

TABLE 4.
Acoustic Measures

	Patients with MTD	Control Participants	*P* Value
Mean Vocal Intensity (dB SPL)	66.95 (3.18)	68.37 (2.55)	**0.0016**†
CPP	4.91 (1.30)	5.31 (0.78)	0.0315†
CPP SD	3.91 (0.77)	4.02 (0.47)	0.3555†
L/H Ratio	32.15 (3.24)	33.13 (2.33)	0.0851†
L/H Ratio SD	12.48 (1.41)	12.64 (1.27)	0.4325*
CPP Fo	203.64 (23.53)	198.45 (19.26)	0.1180*
CPP Fo SD	64.70 (20.11)	64.74 (20.06)	0.8164†
CSID	−3.63 (20.26)	−9.81 (9.87)	0.0783†

† *P* value obtained from a two-sided Mann-Whitney U test for skewed variable distributions.
* *P* value obtained from a two-sided Student's t-test for approximately normally distributed variables.
Comparison of acoustic measures between patients with MTD and vocally healthy control participants. All data reported as mean (SD). *P* values highlighted in Bold refer to comparisons deemed significant at the Bonferroni-corrected significance level of $\alpha = 0.05/16 = 0.003125$.

and expiratory volumes, or cepstral acoustic measures between the two groups.

One explanation for the lack of differences across objective evaluative voice measures between the two groups is the well-cited heterogeneity of MTD.[6,8,34] MTD can present as an aberration to both the sound quality as well as the patient's perception of the feel (discomfort, fatigue, effort) of voicing.[35-37] Because of this variability, author groups have identified aerodynamic profiles of patients diagnosed with MTD. Up to nine distinct aerodynamic profiles have been identified in women with MTD, and only one was characterized as "breath-holding."[8,35,38] However, in our study, 47 (55.3%) patients with MTD had mean airflow values equal to or *greater than* the norms identified in our previous study,[26] suggesting that comparisons of mean airflow to normative values may not be helpful in identifying patients with MTD. Seventy patients (82.4%) of patients in the MTD group produced mean airflow values within two standard deviations around the mean of HC mean airflow values, further highlighting the similarities at the group level. Additionally, the wide range of mean phonatory airflow rates in the normative cohort indicates that vocally healthy adults use a variety of airflow rates, either reduced or increased compared to average, to speak.[38] Future studies and possibly alternative methods of voice analysis are needed to develop means of disentangling the heterogeneity in patients diagnosed with MTD.

Another reason for the lack of significance between groups could have been the task used: reading The Rainbow Passage. Perhaps the lack of communicative intent needed to read a passage did not "trigger" the patient cohort to use a respiratory-phonatory incoordination that may be present in extemporaneous connected speech. However, the patient group in the current study demonstrated greater ranges of phonatory aerodynamic values than the normal group, which may be yet another indicator of the variability of MTD.

Indirectly, our results may corroborate the findings of Gillespie et al, which demonstrated that 19% of participants had a "breath-holding" aerodynamic profile in a syllable-string task as depicted by normal estimated subglottal air pressure (est-P_{sub}) together with low airflow. While the current study used connected speech and did not measure est-P_{sub}, approximately 45% had airflow values that were equal to or lower than the normative data.

Interestingly, the majority of significant differences found in this study were differences in measurements obtained in the *absence of phonation*. Since the two groups overall showed no difference in phonation time but did differ in overall duration of the reading passage, it follows that the significant difference in overall duration is driven by time spent inhaling/exhaling without phonation. This finding could indicate that these patients phonated at higher lung volumes, leading to increased subglottal pressure during voicing. This higher subglottal pressure would necessitate that patients use increased force and tension of the intrinsic laryngeal muscles in order maintain the same rates of airflow during voicing, which could lead to the symptoms of MTD. Previous studies have corroborated this theoretical construct. Gillespie et al found that when challenged with conditions of both hyper- and hypocapnia, subjects maintained phonatory airway laryngeal resistance at the expense of correcting for these gas perturbations.[39] The patients with MTD we studied may be demonstrating the same prioritization of laryngeal resistance maintenance: Since laryngeal resistance is defined as subglottal pressure divided by laryngeal airflow, and laryngeal airflow did not differ significantly between the groups, it follows that the MTD group could have spoken at higher subglottal pressure than the control group. Iwarrson et al also showed that speaking at decreasing lung volumes increased closing quotient while decreasing subglottal pressure.[40] Since laryngeal muscle tension dictates vocal fold length and adduction, it is conceivable that increased lung volumes during phonation in the MTD group led to increased subglottal pressure necessitating increased muscle tension and the subsequent symptomatology of MTD.

Acoustic findings indicated that patients diagnosed with MTD, as a group, sounded essentially "normal" with the exception of a lower intensity. A logical presumption for this and the aforementioned significant increase in overall inhalatory and exhalatory airflow duration could be that although there were no differences in phonatory airflow between groups, the MTD group used a lower intensity and longer inspiratory and expiratory durations which could be thought of as tension in the respiratory-phonatory mechanism, as mentioned above.

At least two limitations of the current study are worth mentioning. First, the MTD cohort of this study was completed as a retrospective voice sample analysis. Aerodynamic and acoustic data analyzed were collected from initial visits of patients from routine voice lab protocols. Future research should be conducted prospectively to control for extraneous factors. We attempted to address this limitation by reanalyzing all voice samples by a single investigator and not relying on the analysis done by SLPs at the time of the clinical visit. More standardized voice recording acquisition could occur with a prospective study design. Second, for acoustic analyses, all voice samples were secondarily analyzed from data recorded using the PAS 6600 system for aerodynamic analyses, which enacts a low-pass filter as outlined in the methods second. Acoustical energies produced above the 10,025 Hz threshold that would normally contribute to acoustic analyses in the Advanced Dysphonia Speech and Voice software would be reduced, which could impact acoustic measurements and therefore comparisons between the two groups. However, data were handled identically in this manner from both the MTD and healthy control groups, so any effects would be equally applied to all patients.

CONCLUSION

Taken in its entirety, connected speech from a sizeable group of patients diagnosed with MTD reflects normal acoustic and aerodynamic values. This study further supports the findings of past work documenting large variability in aerodynamic and acoustic measurements in patients with primary MTD. Prior investigations have identified multiple profiles of phonatory airflow in people with MTD. This study also appears to challenge the alleged aberrant respiratory-phonatory interaction in speech presumed in patients diagnosed with MTD. Individual phonatory aerodynamic and acoustic values should be considered when setting goals and treatment plans for patients with MTD.

Acknowledgment

The authors wish to acknowledge Ali Lewandowski, CCC-SLP, for her help as principal investigator on the original study from which normative data were obtained, as well as for being the voice-specialized SLP to check for interrater reliability in this study.

SUPPLEMENTARY MATERIALS

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.jvoice.2019.12.019.

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