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Endoscopic Assessment of Vocal Fold Movements During Cough

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Objectives: Little is known about the function of the true vocal folds (TVFs) during cough. The objective of this study was to determine the reliability of measuring TVF movements during cough and to obtain preliminary normative data for these measures.

Methods: Sequential glottal angles associated with TVF adduction and abduction across the phases of cough were analyzed from laryngeal videoendoscopy records of 38 young healthy individuals.

Results: The intraobserver and interobserver reliability of 3 experienced measurers was high (intraclass correlation of at least 0.97) for measuring sequential and maximum glottal angles. The TVF abduction velocity during expulsion was significantly higher than the precompression adduction velocity ($p = 0.002$), but there were no significant differences in maximum angle. No statistically significant differences were seen in maximum TVF angle and velocity when they were compared between the sexes and between the levels of cough strength. True vocal fold closure following expulsion occurred in 42% of soft coughs and in 57% of moderate to hard coughs.

Conclusions: The TVF abduction angles during cough can be reliably measured from laryngeal videoendoscopy in young healthy individuals. The TVF movements are faster for expulsion abduction than for precompression adduction, but the extents of abduction are similar. To validly determine the cough phase duration, simultaneous measures of airflow are needed.

Key Words: cough, measurement, true vocal fold movement.

INTRODUCTION

Laryngeal function is vital for phonating, swallowing, breathing, and coughing. Although true vocal fold (TVF) movements have been studied extensively in relation to phonation and swallowing, fewer studies have examined TVF movements during cough.[1-3] Effective cough is a means of airway clearance that defends the lungs from aspiration, reducing the risk of pneumonia and respiratory failure. For instance, studies have shown that a lower peak expiratory cough flow is predictive of failure to extubate,[4,5] risk for aspiration,[6,7] and complications of respiratory infection.[8] In individuals with neuromuscular disease, the ability to cough can be seriously compromised by respiratory muscle and/or laryngeal dysfunction.[9] Cough impairment due to respiratory muscle dysfunction is well understood,[9] but less is known about the effects of laryngeal dysfunction on cough. This lack is, in part, due to an absence of reliable and valid tools for directly measuring TVF mechanics during cough. Objective measures of the extent and speed of TVF movements during phonation, sniff, breathing, and swallowing have been extracted from laryngeal videoendoscopic images.[2,10-15] Although cough involves the same anatomy, it is unknown whether similar methods can be used to determine TVF kinematics during cough. Objective measures are needed to establish normative expectations for TVF movements during cough and to determine how TVF dysfunction may contribute to cough dysfunction in individuals with bulbar impairments. For example, individuals with bulbar amyotrophic lateral sclerosis frequently demonstrate an impaired ability to cough despite having intact respiratory muscle function.[9,16] Cough dysfunction in individuals with bulbar amyotrophic lateral sclerosis is most likely affected by weakness and dyscoordination of the TVFs, resulting in an inability to maintain adequate upper airway patency during cough efforts.[16] Measures such as those proposed in this study will facilitate future study of associations between laryngeal and cough dysfunctions.

A normal cough has 3 sequential phases: inspiration, compression (ie, intrathoracic pressure build),

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TABLE 1. DEFINITIONS FOR ONSETS AND OFFSETS OF COUGH PHASES

Inspiration onset: Assumed to occur after instruction to cough	
Compression onset: Point at which vocal folds or supraglottic structures close	
Expulsion onset: Final frame of maximum closure prior to frame showing abduction (opening)	
Post-cough vocal fold closure onset: Same as "compression onset," above	
Post-cough vocal fold closure end: Final frame of maximum closure before vocal fold opening	

and expulsion (ie, forceful expulsion of air and mucus).[9] Although respiratory muscle strength is critical to cough effectiveness,[9] active TVF movements are also integral to cough physiology and occur synchronously with these phases.[1,2] The TVFs abduct during inspiration, adduct to closure during compression, and abduct again during expulsion. To date, no studies have examined TVF movements during cough in larger subject groups. In addition, no study has included measures that would specifically indicate airway patency, eg, maximum TVF angle during abduction and kinematics of TVF abduction and adduction. Moreover, there have been no comparisons with other factors known to affect phonatory and pulmonary function measures, such as sex and cough strength.

The purpose of this study was threefold: 1) to determine the feasibility and reliability of combined visual-perceptual and objective methods for measuring the duration of cough phases, sequential and maximum TVF abduction angles, and angular velocity of TVF movements associated with inspiration and expulsion phases of cough from laryngeal videoendoscopic images; 2) to provide initial normative data related to TVF movement during cough in young healthy adults; and 3) to explore the influence of sex and cough strength on TVF kinematic measures. This work will provide a basis for future research examining the pathophysiology of cough dysfunction associated with neuromuscular laryngeal impairments.

METHODS

Approval was granted for this study from the University of Washington Institutional Review Board. Video samples of TVFs visualized during cough were extracted from the laryngeal videoendoscopy records of 50 healthy individuals from the University of Washington Speech and Hearing Clinic. The data were obtained during baseline phonatory examinations. The individuals (16 male, 34 female; age range, 18 to 25 years) reported no history of neurologic, voice, or pulmonary dysfunction, except for 1 participant who reported a history of asthma. The smoking status was not available for all subjects. The examinations were conducted by otolaryngologists and speech-language pathologists experienced with laryngeal videoendoscopy. Because the laryngeal videoendoscopic examinations were completed before the data analyses, variations in conditions under which cough were elicited could not be controlled for across individuals. Examinations were conducted with stroboscopic lighting via rigid laryngoscopes (RLS 9100B, KayPENTAX, Lincoln Park, New Jersey), as well as via transnasal flexible laryngoscopes with a distal chip (KayPENTAX VNL 1170K) in some cases. For transnasal flexible laryngeal endoscopy, the nose was decongested and anesthetized with 0.05% Afrin and 4% lidocaine solutions. Some videos contained observations of single coughs, whereas others contained observations of sequential coughs. Individuals examined with transnasal flexible laryngeal endoscopy were instructed to produce both strong and gentle coughs, whereas those examined via rigid laryngoscopy were simply instructed to cough. Participant video records were excluded if they contained no cough data or had inadequate visualization of the TVFs during cough.

Duration of Phases of Cough on Laryngeal Videoendoscopy. To identify the cough phases, videos were viewed frame by frame with Sony Vegas Movie Studio 9.0 software (Sony, Middleton, Wisconsin). The onset times for the following specific phases of the cough were marked: inspiration, compression, expulsion, and, when it occurred, postexpulsion TVF closure. The definitions for the onsets of each of these phases are outlined in Table 1. The duration of each cough phase was then measured in seconds within the constraints of the video sampling rate (30 frames per second).

TVF Angles and Velocities. Video samples of the inspiration and expulsion phases were digitized at 30 frames per second and rendered by frame to image sequences with a frame size of 655 × 480 pixels. With a distance to the screen of 1.5 to 2 feet (about 45 to 60 cm), the examiners marked the TVFs on each frame at the right and left vocal processes and the anterior commissure (Fig 1). The TVF angle was then computed with custom software written with Matlab (Mathworks, Natick, Massachusetts).[13] In instances in which the epiglottis obscured the anterior commissure, the TVFs were marked from the vocal processes to the point at which they could no longer be seen, and the location of the anterior commissure was then computed as the intersection of the two lines. Images were excluded if the view of the TVFs was more than 50% obscured by the epiglot-

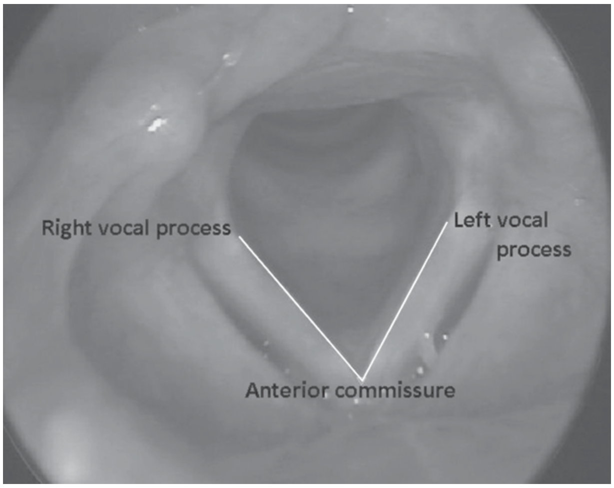


Fig 1. Vocal folds marked for angle computation in Matlab.

tis or by poor camera positioning, or if shadow images prevented accurate identification of the laryngeal structures.

To calculate estimates of TVF adduction and abduction velocity during cough, asymmetric sigmoid curves were fit to sets of sequential monotonic angle data from precompression adduction movements and postcompression abduction, ie, during the expulsion phase, from TVF closure to maximum abduction angle. In a method similar to that reported by Stepp et al,[10] the slope between the points of intersection of the sigmoidal fit with the values 20% and 80% of the maximum angle was used to represent the average velocity.

Finally, observations were made of the pattern of movement of the supraglottic structures during the compression phase, and of whether the TVFs closed after the expulsion phase for all single coughs. For the purposes of comparing the levels of effort, cough observations were divided into soft coughs and moderate to hard coughs based upon auditory perceptual judgments of cough strength made by the primary author (D.B.).

Intra-rater and Inter-rater Reliability. For examination of intra-rater and inter-rater reliability, identification of cough phase durations and markings of the TVFs to calculate angles during inspiration and expulsion phases were repeated by 2 experienced speech-language pathology coauthors (T.E., C.B.) for 10 randomly selected participants. The 2 reliability raters and the primary author completed a portion (10 total) of their ratings twice, with at least 30 minutes between the rating sessions.

Statistical Analysis. The reliability, in terms of absolute agreement, of measuring the abduction angles and the maximum abduction angles was analyzed by use of 2-way random model intraclass correlation coefficients.[17] To avoid correlation induced by multiple cough samples from the same person, 1 random cough sample per participant was selected for the statistical analysis. If the given cough sample contained sequential coughs, the first cough of the sequence was analyzed. Paired *t*-tests were used to compare the maximum TVF abduction angles and the TVF angular velocities between the inspiration and expulsion phases. Independent-sample Student's *t*-tests were used to compare maximum TVF abduction angles and TVF angular velocities across the variables of phase of cough, sex, and cough strength.

RESULTS

After exclusions due to no cough data or inadequate visualization of the TVFs, and exclusion of 1 observation determined to be a reflexive cough, the volitional coughs from 38 of the 50 individuals (11 male, 27 female) were analyzed. For subjects with more than 1 cough observation, 1 observation was randomly selected for analysis. Of this total, 24 coughs were obtained via a rigid scope and 14 via a flexible scope, 26 were single coughs, and 12 were first coughs from multicough sequences. A total of 76 video clips (inspiration and expulsion phases from each cough) were rendered to bitmap frames for analysis. The TVF angle was measured on a total of 994 frames (2% were obscured by the epiglottis; 3% were excluded because of shadow images).

Intraobserver and Interobserver Reliability of Sequential and Maximum TVF Abduction Angles. The intraobserver intraclass correlation coefficients for 91 sequential angles and 10 maximum glottal angles measured from inspiration or expulsion phases of cough across 10 randomly selected participants by 1 of 3 examiners were 0.98 (95% confidence interval [CI], 0.98 to 0.99) and 0.98 (95% CI, 0.94 to 0.99), respectively. The interobserver intraclass correlation coefficients for 104 sequential angles and for 10 maximum glottal angles from inspiratory or expulsion phases of the 10 participants were 0.98 (95% CI, 0.98 to 0.99) and 0.97 (95% CI, 0.94 to 0.99), respectively. Selected examples of interobserver reliability data are presented in Fig 2.

Intraobserver and Interobserver Reliability of Phase of Cough Durations. It was not possible to validly identify the onset of the inspiration phase or the end of the expulsion phase solely from TVF movements, because there were no consistent distinct movements of TVFs at these points. However, phase duration boundaries characterized by TVF closure, ie, compression phase and expulsion phases

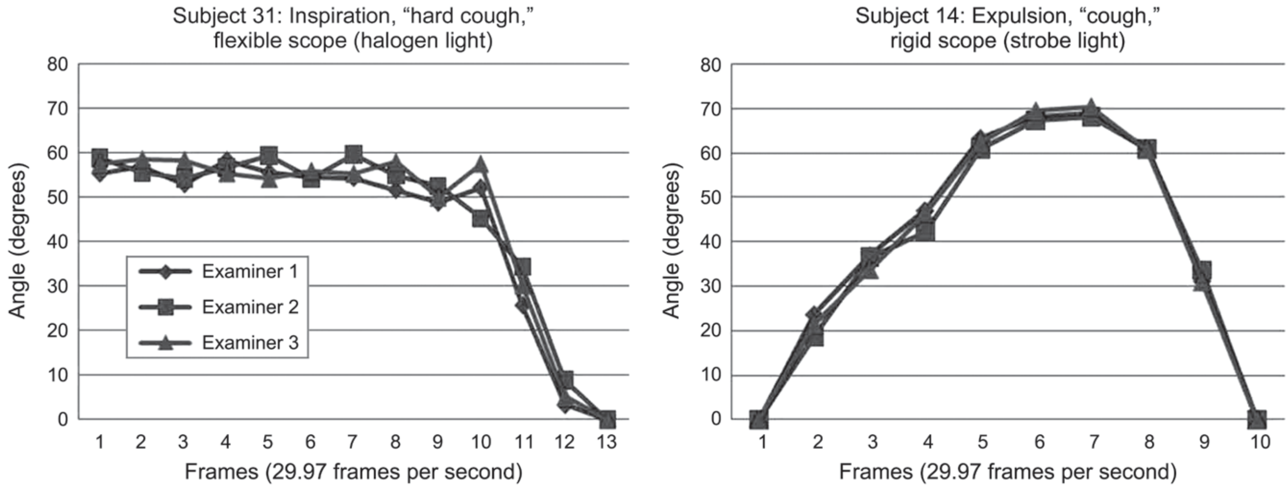


Fig 2. Examples of data collected for interobserver reliability for measurement of vocal fold angles during sequential images from selected inspiration and expulsion phases of cough.

ending with TVF closure, were identified with 100% intraobserver and interobserver reliability.

Maximum TVF Abduction Angle During Cough. The maximum TVF angles were compared between the inspiration and expulsion phases of cough within 36 subjects and between groups defined by sex and cough strength (38 subjects for inspiratory phase; 36 subjects for expulsion phase). No statistically significant differences were observed between maximum abduction angles during the inspiration phase versus the expulsion phase ($p = 0.27$; Table 2). No statistically significant differences were seen in comparing maximum abduction angles between the groups defined by sex ($p = 0.06$ for inspiratory phase; $p = 0.15$ for expulsion phase) and by cough strength level ($p = 0.24$ for inspiratory phase; $p = 0.07$ for expulsion phase). However, differences in maximum TVF angle approached significance between the sexes during the inspiratory phase, with women (mean, 49.8°; SD, 14.3°) demonstrating slightly wider maximum TVF angles than men (mean, 36.8°; SD, 19.3°), and between cough strengths during the expulsion phase, with wider maximum TVF angles observed during moderate to hard coughs (mean, 54.9°; SD, 12.9°) versus soft coughs (mean, 46.6°; SD, 12.9°).

TVF Velocity of Movement During Cough. The sequential angle data from precompression adduction and expulsion abduction were monotonic and fit well by an asymmetric sigmoid curve (Fig 3). Using these data, average TVF precompression adduction and postcompression abduction angular velocities were compared within 34 subjects and between groups defined by the variables of sex and cough strength (37 subjects for inspiratory phase; 35 subjects for expulsion phase; Fig 4). The postcompression abduction average velocity (mean, 996°/s; SD, 811°/s) was statistically higher than the precompression adduction average velocity (mean, 541°/s; SD, 309°/s; $p = 0.002$). No significant differences were observed in comparing average TVF precompression adduction and postcompression abduction angular velocities across the variables of sex ($p = 0.60$ for inspiratory phase; $p = 0.58$ for expulsion phase) and cough strength ($p = 0.22$ for inspiratory phase; $p = 0.93$ for expulsion phase).

TVF Closure Following Expulsion Phase of Cough. The presence of TVF closure following expulsion for 26 single-cough samples was observed and compared with differences in cough strength. Overall, postexpulsion TVF closure occurred in 46% of observed coughs. When closures were compared as a function of cough strength, however, postexpul-

TABLE 2. MAXIMUM ABDUCTION ANGLES

		Angles (°)	
Cough Phase	*n*	*Mean*	*SD*
Inspiration	36	47.1	16.4
Expulsion	36	50.0	13.4

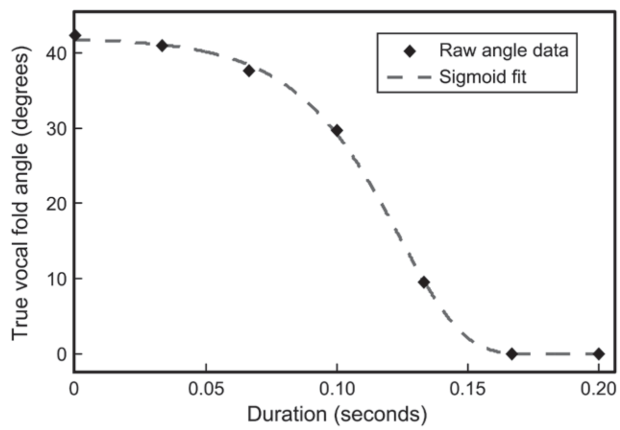
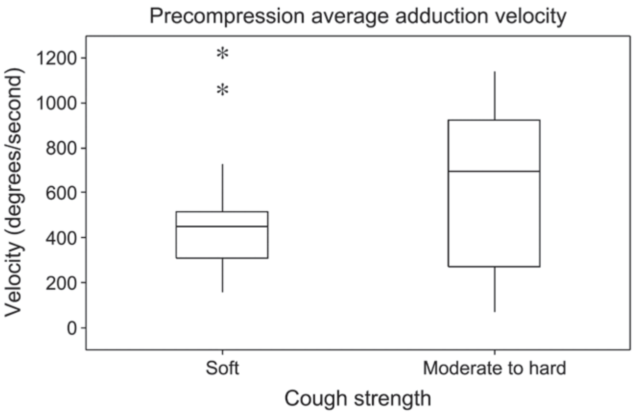


Fig 3. Example of sequential true vocal fold adduction angle data for 1 subject, fit to asymmetric sigmoid curve.



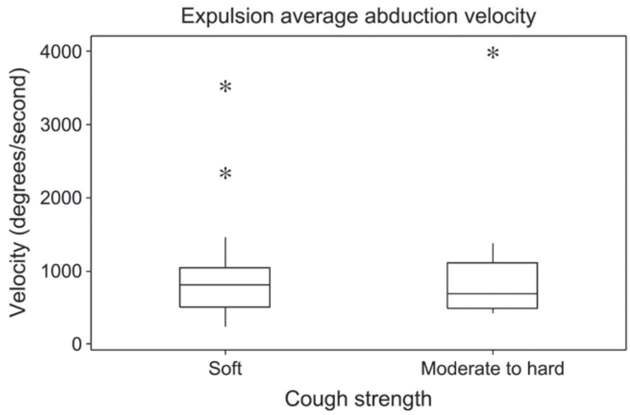


Fig 4. Angular velocity; precompression adduction versus postcompression (expulsion) abduction. Boxes represent median and interquartile range. Whiskers extend to lowest and highest data values within 1.5 times interquartile range from box edges. Any values located further than 1.5 times interquartile range past box edges are indicated by asterisks.

sion TVF closure occurred for 42% (8 of 19) of the soft coughs observed and for 57% (4 of 7) of the moderate to hard coughs observed.

Movements of Supraglottic Structures During Cough. The patterns of TVF and supraglottic movements during the compression phase of cough were observed. Across 95% (36 of 38) of all coughs, a consistent dynamic pattern of supraglottic reinforcement of airway closure was observed. After closure of the TVFs, closure of the supraglottic structures was achieved via extreme anterior-posterior compression (ie, arytenoids contacted the petiole of the epiglottis) and medialization of the false vocal folds. These movements were further aided by squeezing of the pharyngeal walls, creating a supraglottic sphincter. Upon expulsion, the supraglottic structures and the TVFs popped open together within the time span of a single frame (ie, approximately 0.03 second). In a very small number of observations (approximately 5%), TVF closure was observed without additional supraglottic closure; these were all very soft cough observations.

Cough Phase Duration. Cough phase durations were compared across 26 single-cough observations; sequential-cough samples were omitted from this analysis. It was not possible to collect valid data on the duration of the inspiration phase without airflow data. Observation of the expulsion phase duration was limited to 12 single coughs in which postexpulsion TVF closure was observed. The expulsion phase durations were generally less variable than the preexpulsion and postexpulsion compression phases (Table 3).

DISCUSSION

The results from this study support the feasibility and reliability of a method used to visualize and measure sequential TVF angles during cough. This study is the first to report a successful methodology for visualization and measurement of TVF kinematics during cough. In addition, despite the sampling rate constraints, it was possible to calculate the velocity of TVF motion for precompression adduction and expulsion abduction angle sequences, as these data were monotonic and fit well by an asymmetric sigmoid curve (Fig 3).

Measuring cough phase duration from observation of TVF movements proved more difficult. The TVFs were typically in an abducted position just before the instruction to cough. Further abduction movements were subtle, and it was not possible to visually detect the direction of airflow solely by frame-by-frame visual inspection of the endoscopic video. For this reason, the onset of "inspiration" was artificially defined as being after the instruction to cough. The compression phase could be visualized, as it involved airway closure by the TVFs and the supraglottic structures. The onset of the expulsion phase was determined by the end of the compression phase. However, we could not determine the end of the expulsion phase for subjects who did not demonstrate TVF closure after the cough. To obtain valid measures of cough phase durations, it is necessary to link TVF movements to airflow data.

No statistically significant differences were observed in the maximum abduction angle between the inspiratory and expulsion phases or between groups defined by sex and cough strength. These findings

TABLE 3. DURATIONS OF PHASES OF COUGH

		Duration (s)		
Cough Phase	*n*	*Mean*	*SD*	*Range*
Preexpulsion compression (true vocal fold closure)	26	0.33	0.22	0.07-0.97
Expulsion	12	0.24	0.06	0.13-0.37
Postexpulsion compression	9	0.26	0.36	0.00-0.83

TABLE 4. MEAN ANGULAR VELOCITIES DURING COUGH AND DURING SPEECH REPETITION TASK

	Cough		Sniff-/i/ Repetitions at Fast Rate*	
Cough Level of Effort or Strength	Precompression Adduction	Expulsion Abduction	Adduction	Abduction
Overall	533 ± 300	980 ± 805	481 ± 99	398 ± 83
Soft	479 ± 257	970 ± 744		
Moderate to hard	613 ± 347	995 ± 918		

Velocities are presented in degrees per second (mean ± SD).
*Data from Stepp et al.[10]

are contrary to those of studies of pulmonary function and phonatory measures that show statistically significant differences between the sexes[18,19] and an effect of effort on pulmonary function measures.[19] It is possible that these measures have a higher level of variability and/or that these results were influenced by poor control over data in this secondary data analysis. Therefore, future prospective controlled studies are needed to confirm or refute these exploratory results.

The TVF abduction velocity during the expulsion phase was faster and more variable than the precompression adduction velocity. In comparing TVF adduction and abduction velocities observed during cough with the TVF velocities associated with speech (ie, fast sniff-/i/ repetitions) reported by Stepp et al,[10] we found that the cough-related TVF velocities were much faster and more variable (Table 4). Additionally, the inspiratory adduction and, especially, expulsion abduction velocities were relatively unchanged with increases in cough strength. The observation of a higher abduction velocity with expulsion that is relatively unaffected by cough strength is consistent with physiological findings reported by Hillel,[1] who observed an overlap of intrinsic laryngeal muscle adductor and abductor electromyographic activities approximately 150 ms before expulsion abduction. Hillel[1] explained that this activity effectively "spring loads" abduction movements to occur at the instant the intrinsic adductor laryngeal muscles relax. The timing of the TVF actions during the expulsion phase of cough suggests that the mechanism is reflexive in nature, even when the movement is initiated volitionally. The ability of the laryngeal muscles to coordinate so quickly in concert with the muscles of respiration during cough expulsion is a life-preserving reflexive response that serves to protect the airway and lungs.[20]

After the expulsion phase of cough, TVF closure occurred inconsistently, but occurred more frequently with moderate to hard coughs than with soft coughs. This observation may explain contrary findings in prior studies, in which reports of TVF closure after the expulsion phase with single coughs were mixed.[1-3] Further studies will be needed to determine whether cough strength is a significant factor influencing TVF closure after cough expulsion. The TVF closure following cough expulsion may further protect the airway under conditions of more effortful coughing and/or reflexive coughing.

A consistent, dynamic pattern of supraglottic movements was observed to reinforce the pre-expulsion TVF closure across 95% of participants. Within the context of phonation, supraglottic involvement is typically interpreted as a sign of dysfunction. However, similar supraglottic reinforcement of laryngeal closure has been reported with effortful breath-holding[21] and swallowing.[22] Supraglottic closure is necessary to prevent air escape during the compression phase of cough.

This study is the first to specifically measure TVF movements during cough and to explore the potential effect of relevant factors on these measures. However, because these data were analyzed after clinical examinations, many variables were uncontrolled, as the clinicians did not follow a uniform data collection protocol. Although the participants examined via a rigid laryngoscope were positioned differently, ie, with the head and neck more anterior and the tongue protruded, we did not observe any overt variation in the cough mechanism itself. We also did not observe any gagging associated with cough tasks for those examined with rigid laryngoscopes. Owing to the lack of uniformity in task instructions, auditory perceptual judgments of cough strength made by the primary author were used to indicate cough strength. Further study is needed to check for the consistency of these judgments between clinicians, and to correlate these judgments with objective measures of cough strength such as peak expiratory cough flow. The lack of airflow data made computation of cough phase durations inadequate. Future studies that link TVF kinematic data with airflow are needed to determine associations between TVF movement patterns and the resulting peak expiratory cough flow. In addition, future work using a single protocol for the type of scope, consistent task instructions to elicit soft versus hard levels of effort, and a systematic number of trials per subject would strengthen this research effort. Despite the lack of control in data collection, this report of exploratory findings based upon secondary analysis of data collected clinically provides preliminary information to aid research hypotheses for future controlled studies using the novel measures described in this study.

CONCLUSIONS

The TVF angle during cough can be reliably measured from endoscopic images. Additional airflow data are needed for measures of the duration of cough phase.

Exploratory analyses suggest that the average velocities of TVF movements may be faster for expulsion abduction than for precompression adduction, whereas the extents of TVF abduction are relatively similar. Sex and cough strength had no statistically significant effect on the speed or extent of TVF movements during cough. Closure of the TVFs following expulsion occurred inconsistently, and was more frequent with moderate to hard coughs than with soft coughs. Finally, during the compression phase of cough, the supraglottic structures typically closed completely after TVF closure. This action effectively reinforced the tight closure of the airway during the compression phase.

Additional research is needed to determine optimal methods for measuring laryngeal function during cough. Specifically, well-designed studies with a single data collection protocol are needed, with simultaneous laryngeal and airflow data. Application of these measures to future research in individuals with laryngeal dysfunction resulting from neurologic disorders, such as amyotrophic lateral sclerosis, multiple sclerosis, cerebral palsy, paradoxical TVF motion, and/or stroke, would further elucidate the specific pathophysiology involved in cough dysfunction in these clinical populations.

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