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Post-laryngectomy speech respiration patterns

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Abstract

Objectives—The goal of this study was to determine if speech breathing changes over time in laryngectomy patients using an electrolarynx, and to explore the potential of using respiratory signals to control an artificial voice source.

Methods—Respiratory patterns during serial speech tasks (counting, days of the week) with an electrolarynx were prospectively studied in six individuals across their first 1–2 years after total laryngectomy, as well as in an additional eight individuals at least 1 year post-laryngectomy using inductance plethysmography.

Results—In contrast to normal speech that is only produced during exhalation, all individuals were found to engage in inhalation during speech production, with those studied longitudinally displaying increased occurrences of inhalation during speech production with time post-laryngectomy. These trends appear to be stronger for individuals who used an electrolarynx as their primary means of oral communication rather than tracheoesophageal (TE) speech, possibly due to continued dependence on respiratory support for the production of TE speech.

Conclusions—Our results indicate that there are post-laryngectomy changes in electrolarynx speech breathing behaviors. This has implications for designing improved electrolarynx communication systems, which could use signals derived from respiratory function as one of many potential physiologically based sources for more natural control of electrolarynx speech.

Keywords

breathing; alaryngeal; electrolarynx; tracheoesophageal speech; inductance plethysmography

Introduction

A majority of laryngectomy patients in the United States use an electrolarynx (EL) to communicate^{1–4}, but EL devices are cumbersome to use (i.e., requiring the use of one hand) and EL speech has reduced intelligibility and poor/unnatural quality⁵. For several years our group has been investigating multiple approaches for improving EL speech communication^{2, 5–11}, including the use of signals that are related to speech physiology as a basis for providing more natural control of an EL device^{6–9}. One potential source of such control signals is the respiratory system because of well-defined relationships between respiratory kinematics and speech production in normal speakers (e.g. Hixon¹²). Thus, the

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purpose of this study was to determine the potential for using respiratory-related signals to control an EL in individuals after laryngectomy. This was done by examining respiratory function during electrolarynx speech in post-laryngectomy patients that use either an electrolarynx, or an aerodynamically driven form of alaryngeal speech (esophageal or tracheoesophageal) as their primary means of communication.

In individuals with normal voice and speech, respiration is coordinated with the intent to speak. While the kinematics of speech breathing have been studied extensively for different speech tasks and in differing groups^{12–15}, the most obvious requirement of speech respiration in most populations is generating an adequate exhalation to create sound at points of articulatory constriction and drive the vocal folds into motion, thereby valving the air stream for the production of voice. After laryngectomy, the airway is separated from the pharynx and an alaryngeal voice source is needed to speak. In EL users, voice and speech production are no longer dependent on the respiratory system. Conversely, individuals using tracheoesophageal (TE) or, to a lesser degree, esophageal speech still maintain some physical relationship between the respiratory system and the production of voice and speech.

Given the drastic changes in aerodigestive tract anatomy experienced by laryngectomized individuals, speech breathing patterns may be expected to change over time, particularly for individuals who exclusively use an EL to speak. However, Liu et al.¹⁶ reported that while individuals 2 – 3 months post-laryngectomy (N=8) were still likely to exhale during speech, individuals 5 – 11 years post-laryngectomy (N=4) were likely to hold their breath during speech. Surprisingly, they reported that it was very rare for their participants to inhale during speech tasks, regardless of time post-surgery, and even when asked to do so. This finding conflicted with our previous informal observations that breathing patterns are often independent of EL speech.

Speech breathing patterns in laryngectomized individuals have implications for the development of EL technology based on respiratory control, motivating the present investigation. If the respiratory kinematics after laryngectomy prove to be adaptable, the design of EL technology utilizing respiratory signals is less limited with respect to control schemes; however, if breathing patterns are stable after laryngectomy, control scheme design will be dependent upon these specific respiratory kinematics. The breathing patterns of six laryngectomized individuals across their first 1–2 years after total laryngectomy and those of eight individuals at least one year after total laryngectomy were recorded using respiratory inductance plethysmography during serial electrolarynx speech tasks (i.e. counting 1–10 and saying the days of the week) to quantify their speech breathing patterns in relation to time post laryngectomy.

Materials and Methods

Participants were fourteen laryngectomized individuals (2 females, 12 males) between the ages of 41 and 80 years at the time of their last (or only) recording session. From April 2000 to April 2006, a prospective assessment of speech breathing was conducted on six individuals undergoing total laryngectomy (Longitudinal Group). Based on the trends seen in these original data, from April 2007 to September 2007, eight individuals at least one year post total laryngectomy were also recorded (Single Time-Point Group). These study protocols were approved by the human studies institutional review boards of the Massachusetts General Hospital and the Massachusetts Eye and Ear Infirmary.

The demographic information, recording sessions, and primary mode of communication are detailed across participants in Table 1. The six individuals in the Longitudinal Group were recorded across their first year after total laryngectomy with time periods that varied by

individual, but ranged from one month post-laryngectomy to 31 months post-laryngectomy. All of these individuals were recorded at three or more different time points, with an average sampling of 4.5 visits, and all were recorded at least as early as 5 months post-surgery. Two of these six individuals became proficient TE speakers during the recording period (TE1 by month 8 and TE2 by month 5). The individual ES1 was a proficient user of esophageal speech by month 11, but communicated with a combination of esophageal and EL speech. Individuals comprising the Single Time-Point Group were recorded at least one year post laryngectomy. Of these individuals, two were proficient users of TE speech, and had used TE speech as their primary mode of communication for at least one year (while maintaining an EL for backup communication). The remaining six individuals used EL speech as their primary mode of communication. All individuals (N=14) reported themselves as nonsmokers during the time of the experiment, without history of language, hearing or speech disorders (prior to laryngectomy) and were proficient users of EL speech, even if it was not their primary mode of communication.

Simultaneous acoustic signals and thorax/abdomen movement signals were filtered and recorded digitally (20,000 Hz sampling rate) with Axon Instruments hardware (Cyberamp 380, Digidata 1200) and software (Axoscope). The acoustic signal was obtained from a lavalier microphone (Sony ECM50PSW) or headset microphone (AKG Acoustics C 420 PP). Thoracic and abdominal wall movement was recorded using two flexible inductance bands that fit around the chest and abdomen (Respirtrace Systems). During setup, kinematic data were checked to ensure that the full breathing range was within the amplitude range of the recorded signals and that increases in signal strength corresponded to chest and abdominal band expansion. Attempts were made in three individuals to use a fixed volume calibration bag (#910-0185-000; VivoMetrics, Ventura, CA) to calibrate the respiratory signals, but air leakage around the calibration bag's tube placement against the tracheostoma prevented consistent measurement of a fixed volume exchange in all but one individual. These calibration attempts did, however, validate the assumed relationship between respiratory signal deflection and direction of air flow from the stoma (inhalation/exhalation). Isometric respiratory calibration maneuvers were not performed due to the difficulties associated with achieving airway closure in neck-breathing individuals (i.e. air leakage around stomal occlusion and air passage through TE valves when present). Therefore, kinematic data were used to observe the direction of chest wall motion only, with the goal of identifying regions of inspiration during speech, as is discussed subsequently.

All participants were able to complete serial speech tasks using an electrolarynx without difficulty, regardless of their primary alaryngeal voice source. These speech tasks consisted of saying the days of the week and counting to ten. Participants were instructed to pause (turn off the EL) between each word. Although the instruction to pause between words elicits speech behavior that is perhaps less natural than running speech, it facilitated accurate analysis of respiration patterns for vocal production versus pauses which are otherwise often obscured by continuous EL activation on the part of the user. However, in order to compare the behavior quantified during serial tasks with that in the more natural context of running speech, individuals were also recorded while reading the first paragraph of "The Rainbow Passage"¹⁷.

The extent to which inspiration occurred during speech was calculated as a percent of total EL voiced speech time for each individual at each recording session. The abdominal and thoracic kinematic data were analyzed with respect to slope, with positive slopes indicating inspiratory movements. Because of the possible occurrence of paradoxical movement during breathing, inspiration was marked at those times when both the abdominal and thoracic band displayed positive slope. This likely resulted in an underestimation of inspiration time, but ensured that behavior identified as inspiration was unequivocally inspiration.

Speech time during the serial speech tasks was determined by visual and acoustic identification of EL activation in the microphone signal using custom software written in MATLAB (Mathworks Inc., Natick, MA) without simultaneous observation of respiration signals. Speech time during the Rainbow Passage was determined by adjusting an audio amplitude threshold of the recorded passage, which removed low-amplitude (sub-threshold) sounds while maintaining supra-threshold sounds. The threshold was adjusted for each recording (by the first author) until the resulting speech was intelligible but lacked the low-amplitude EL buzzing associated with a closed mouth. This approach erred towards removing some low-amplitude speech components, yet ensured that non-speech periods were not included in the speech time.

To screen for obvious evidence of compromised respiratory function, all subjects were recorded “at rest” to obtain their tidal breathing rates. The average breaths per minute (BPM) were calculated for each subject by visually selecting isolated inspirations during tidal breathing.

Results

All participants deviated from natural speech breathing patterns, though their speech breathing patterns varied qualitatively. Some individuals displayed breathing that was obviously modulated by the intent to speak, but was some degree out of phase with natural behavior. For example, they were noted to begin speaking prior to their peak in inspiration during what would otherwise look like a normal pre-phonatory inspiration. In other individuals, speech breathing patterns approximated those of tidal breathing or were extremely atypical, including relatively long periods of breath holding interspersed with randomly placed large inspiratory and expiratory excursions. Looking at the speech breathing behavior more quantitatively, Figure 1 shows the percent of EL speech time during which all participants ($N = 14$) inhaled during serial speech tasks as a function of their time post-laryngectomy. All participants spent some portion of their speech time inhaling, with individual values ranging from 8% to 64%. Analyses of respiration during reading of the Rainbow Passage confirmed the presence of inhalation during running speech, with individual values ranging from 10% to 44%. The remaining results presented below pertain exclusively to the serial speech tasks (isolated words) due to the higher confidence in differentiating speech versus non-speech time.

Longitudinal Group Results

For the six individuals comprising the Longitudinal Group, an average change in the percent of EL speech time during which the participant inhaled was calculated for the final recording session (8 – 31 months) versus the point closest to 4 months post-laryngectomy. Although there were data available for some individuals earlier than 4 months, the 4 month time point was chosen because it was the most frequently occurring sample point in the early post-surgical time period (e.g. < 6 months). All of these individuals were found to engage in inspiration during EL speech production with increasing amount as their time post-laryngectomy progressed. The average increase in the percent of EL speech time spent inhaling across all participants was 19%, which was statistically significant at $p < 0.01$ (one-tailed t-test). Figure 2 illustrates the difference seen in the raw data for one EL participant (EL3) at 4 months and 12 months post-laryngectomy. When the Longitudinal Group participants are grouped by their primary alaryngeal communication mode of EL ($N = 3$) or TE/esophageal ($N = 3$), the data indicate that the individuals who primarily used TE or esophageal speech may have maintained more natural speech breathing compared to their EL-using counterparts when all participants used an EL. The average increase in the percent of EL speech time spent inhaling for the three TE/esophageal speech participants was 12% (SD 0.6%); whereas the three EL users had more than twice that degree of change, with an

average increase of 27% (SD 2%) over time. However, a statistical comparison between these average subgroup changes over time ($N = 3$ per sub-group) failed to find a significant difference ($p = 0.11$; one-tailed t-test).

Longitudinal and Single Time-Point Group Results Combined

The last post-surgical data point collected for all participants ($N=14$) is shown in Figure 3. The average percent of speech time spent inhaling for all participants was 28% (SD 17%), which is statistically greater than zero (one-tailed t-test, $p < 0.001$). These data also support the trend that TE and esophageal speakers display less inhalation during speech than EL speakers. The TE and esophageal speakers spent an average of 19% (SD 9%; $N = 4$) of speech time inhaling, while EL speakers spent an average of 33% (SD 19%; $N = 10$) of speech time inhaling (with all subjects using an EL), producing a statistically significant difference ($p = 0.04$, one-tailed t-test). For the last post-surgical data point collected for all participants, the BPM was compared to the percent of speech time spent inhaling. However, no correlation was found between these two measures ($R^2 = 0.03$). Further, no difference in BPM was found between EL and TE/esophageal groups ($p = 0.42$, one-tailed t-test) with EL users displaying an average tidal breathing rate of 18.5 BPM (SD 6.2 BPM) and TE users 19.3 BPM (SD 7.4 BPM).

Discussion

This study provides insight into changes in speech breathing associated with post-laryngectomy use of an electrolarynx. In contrast to normal speech that is only produced during exhalation, the results indicate that the relationship of respiratory phase (i.e., inhalation versus exhalation) to volitional EL speech becomes variable after laryngectomy. Moreover, although all participants performed speech tasks with an EL in this study, the amount of time they spent inhaling during speech depended somewhat on their typical (primary) mode of alaryngeal communication.

The results of the present study differ considerably from Liu et al.¹⁶ who did not observe inspiration during the speech of the laryngectomized individuals in their study. Even with our conservative estimate of the time spent inhaling during speech (simultaneous positive slopes on both abdominal and thoracic bands), it was obvious that our participants spent a sizeable percentage of their time speaking on inhalation. However, the finding by Liu et al. that individuals who were 2–3 months post-laryngectomy found it difficult to speak with an EL while independently inhaling and exhaling is not contradicted by our data. Our longitudinal data display a lower incidence of inhalation during speech at 2 or 3 months after surgery than later time points, perhaps reflecting that speech breathing patterns learned over a lifetime are still active and that individuals may resist performing “unnatural” speech breathing tasks. However, we do not have an explanation for the differences between our data and the findings of Liu et al. in their four individuals 5 – 11 years post-laryngectomy. While their participants (fulltime EL users) were not seen to inhale during natural speech and even found it impossible to learn to inhale and exhale independently while speaking with an EL, our EL participants did so frequently by their final data point (8 – 204 months; see Table 1) without having received any instruction regarding their breathing patterns.

The present findings indicate that speech breathing not only changes after laryngectomy, but also does so to a degree which generally relates to speech breathing requirements in the post-surgical period. The laryngectomized individuals who relied exclusively on an EL as their alaryngeal voice source experienced a total loss of physical coupling between alaryngeal voice production and exhalation, and also spent the greatest percentage of speech time inhaling, especially at 8 months or more after laryngectomy. In contrast, the laryngectomized individuals who initially used an EL but came to produce TE ($N = 4$) or

esophageal (N = 1) speech during their first post-surgical year needed to coordinate breathing with their primary means of alaryngeal speech, and consequently either maintained or re-learned a more normal speech breathing pattern by their last recording session. This was demonstrated by the fact that although the use of an EL during the speech tasks in this study permitted indiscriminant breathing patterns, the TE/esophageal subjects (on average) demonstrated less inhalation during EL speech than subjects who typically spoke with an EL ($p = 0.04$, one-tailed t-test). This finding suggests that an artificial voice control strategy that depends on normal speech breathing patterns may work best if initiated early in the post-surgical period, or may require a period of training to extinguish instances of inhalation during speech production.

One possible explanation for altered breathing patterns in EL users versus TE/esophageal speakers is inferior pulmonary function in the EL user population. Inadequate pulmonary function is one of several reasons why laryngectomees are sometimes unable to adopt TE speech (for reviews see ^{18–20}), potentially increasing the likelihood of our EL group having more individuals with compromised pulmonary function could lead to their increased inhalation during speech. However, no correlation was found between these two measures, and no difference in BPM was found between EL and TE/esophageal groups. Further, the average BPM found in both of these groups are less than one standard deviation of the average tidal breathing rate of a group of 50 year old healthy speakers (13.7 BPM, SD 4.7 SD, N = 30), indicating a lack of obvious evidence that poor respiratory health (i.e., a need to inhale more frequently) was likely not a role in the tendency of some of the subjects to inhale during speech production ²¹.

The increased appearance of inhalation during EL speech production over time after laryngectomy in a communication mode-dependent manner is not surprising given the flexibility that anatomically normal individuals have over speech-related respiration. As an extreme example, some individuals learn to habitually speak on inhalation (i.e. “reverse phonation”) as a rehabilitation technique for laryngeal focal dystonia ²². This ability is consistent with the known importance of auditory targets for speech production^{23–25}, and changes in speech breathing that result from abnormal hearing ²⁶ suggest that the targets for speech breathing are auditory as well. Thus, it is not unexpected that the strict coordination between exhalation and speech is abandoned once exhalation is not necessary to produce the required auditory target.

Evidence of the primacy of auditory feedback to speech breathing behavior supports the potential for developing EL control systems that are respiration-based. Perhaps if the respiration is once more linked with audible speech production, the inherent flexibility of the respiratory system in supporting speech will facilitate the adoption of breathing patterns advantageous for more naturally controlling an artificial voice source. However, prior research by Uemi et al.²⁷ indicates that the dissociation between breathing and speaking may be resistant to change. They studied the ability of sixteen laryngectomees with varying primary alaryngeal voice sources to control pitch and timing of an electrolarynx with respiration. They found that after one week of training (30 minutes a day), only six of fourteen participants were able to control the on/off timing of the device within 500 ms, and only three of fourteen participants were able to control the pitch of the device in order to match a given a two-pitch stimulation signal. Although the time post-laryngectomy of these participants was not reported, there were six individuals studied who used TE speech as their primary alaryngeal voice source. The performance of these individuals was somewhat better than the entire cohort studied, with four of these individuals able to control the on/off timing within 500 ms, and two able to control the pitch of the device. Thus, the present results indicate that speech breathing patterns after laryngectomy relate to speech breathing demands (i.e. EL vs. TE speakers speech breathing patterns), suggesting that further studies

regarding specific respiratory-driven control schemes are needed to fully explore the possibilities of a respiration-controlled electrolarynx.

Conclusions

Our results suggest that speech breathing associated with electrolarynx use after laryngectomy changes over time and that perhaps new speech breathing patterns could be learned. Furthermore, the observation that breathing patterns differed during EL speech based on a person's primary means of alaryngeal speech, and presumably their typical speech breathing demands, has implications for the design of, and training needs for physiologically controlled EL technology, which could use signals derived from respiration as a basis for more naturally controlling EL speech.

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Figure 1.

The percent of total speech time spent inhaling is plotted for all participants as a function of the time after their laryngectomy surgery. Individuals whose primary source of alaryngeal voicing is TE or esophageal speech are indicated by solid tokens (triangles for TE speakers and circles for esophageal speakers), while individuals whose primary source of alaryngeal voicing is EL speech are indicated by open square tokens.

Figure 2.

Example of raw data for participant EL3 at 4 months and 12 months post-laryngectomy. The top panel shows the audio signal as the individual counts from 1 – 10. The middle and lower panels show kinematic data. Grey overlays highlight instances of inhalation during speech. Participant EL3 inhaled 19% of speech time at 4 months post-laryngectomy and 64% of speech time at 12 months post-laryngectomy.

Speech Inhalation - Last Datapoint

Figure 3.

The percent of total speech time spent inhaling for the final data point of all participants as a function of the time after their laryngectomy surgery. Individuals whose primary source of alaryngeal voicing is TE or esophageal speech are indicated by black columns, while individuals whose primary source of alaryngeal voicing is EL speech are indicated by grey columns.

Table 1

Participant demographic information and recording sessions.

Participant	Research Group	Age at Last Recording (Years)	Sex	Recording Sessions (Months Post-Surgery)
EL1	Longitudinal	64	M	4, 6, 8, 12
EL2	Longitudinal	41	M	2, 4, 6, 8, 12
EL3	Longitudinal	71	M	2, 4, 6, 8
TE1	Longitudinal	62	M	4, 6, 8, 12
TE2	Longitudinal	61	M	1.5, 3, 8, 31
ES1	Longitudinal	71	M	5, 11, 15
EL4	Single Time Point	80	M	204
EL5	Single Time Point	60	F	156
EL6	Single Time Point	62	M	15
EL7	Single Time Point	60	M	30
EL8	Single Time Point	61	M	26
EL9	Single Time Point	54	M	18
TE3	Single Time Point	48	F	14
TE4	Single Time Point	64	M	53

EL—electrolarynx, TE—tracheoesophageal, ES—esophageal