Aerodynamic and Acoustic Features of Vocal Effort

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Summary: Objectives. The purpose of this study was to determine the aerodynamic and acoustic features of speech produced at comfortable, maximal and minimal levels of vocal effort.

Study Design. Prospective, quasi-experimental research design.

Method. Eighteen healthy participants with normal voice were included in this study. After task training, participants produced repeated syllable combinations at comfortable, maximal and minimal levels of vocal effort. A pneumotachometer and vented (Rothenberg) mask were used to record aerodynamic data, with simultaneous recording of the acoustic signal for subsequent analysis. Aerodynamic measures of subglottal pressure, translaryngeal airflow, maximum flow declination rate (MFDR), and laryngeal resistance were analyzed, along with acoustic measures of cepstral peak prominence (CPP) and its standard deviation (SD).

Results. Participants produced significantly greater subglottal pressure, translaryngeal airflow, and MFDR during maximal effort speech as compared with comfortable vocal effort. When producing speech at minimal vocal effort, participants lowered subglottal pressure, MFDR, and laryngeal resistance. Acoustic changes associated with changes in vocal effort included significantly higher CPP during maximal effort speech and significantly lower CPP SD during minimal effort speech, when each was compared with comfortable effort.

Conclusions. For healthy speakers without voice disorders, subglottal pressure, translaryngeal airflow, and MFDR may be important factors that contribute to an increased sense of vocal effort. Changes in the cepstral signal also occur under conditions of increased or decreased vocal effort relative to comfortable effort.

Key Words: Voice–Aerodynamic–Acoustic–Vocal effort–Cepstral–Pressure–Airflow–Laryngeal resistance–Maximum flow declination rate.

INTRODUCTION

Effortful voice production is a critical component of many voice disorders, yet the physiology that contributes to this sense of effort has been minimally studied. Vocal effort is often perceived by others as a strained voice quality[1] and is considered to be a component of vocal hyperfunction.[2] The increased vocal effort that occurs in hyperfunctional voice disorders can be associated with a number of physiological states, such as altered patterns of intrinsic and extrinsic laryngeal muscle activation, attempts to compensate for a lack of vocal fold closure, altered respiratory behavior, or other changes in the vibratory patterns of the vocal folds. Because of the multiple physiological contributions that can produce increased vocal effort, the quality of strain is evidenced across a variety of voice disorders.

Nonorganic, organic, and neurologic voice disorders can alter closure patterns or muscle activation patterns during vocal fold vibration, with subsequent perceptual consequences of strained voice quality and increased vocal effort. Effective treatment of these disorders targets optimal voice quality and vocal function while promoting phonatory behaviors that minimize vocal effort. Outcome data for treatment efficacy often include an assessment of change in self-perceived effort from pre- to posttreatment time points.[3,4] By determining the physiological changes that contribute to increased vocal effort, treatment approaches can be tailored to modify specific phonatory behaviors with the goal of minimizing vocal effort. Studying the effects of systematic changes in vocal effort on phonatory behavior is difficult in people with voice disorders because they present with chronically increased vocal effort and are therefore unable to vary that effort between minimal, comfortable, and maximal levels. Instead, by focusing on healthy individuals without voice disorders, we can determine the critical components of phonatory function that differentiate voice produced with maximal or minimal vocal effort from that produced at a comfortable level of effort.

Changes in vocal fold compression and laryngeal muscle activity during phonation are thought to produce the perceptual outcomes of increased vocal effort and strain, yet little is known about the relative contributions of laryngeal physiological variables to vocal effort. Rapid changes in laryngeal muscle activation occur with air pressure stimulation to the laryngeal mucosa.[5–7] Thus, subtle changes in laryngeal pressure, airflow, and laryngeal constriction can all provide sensory feedback related to vocal effort. Human physiology studies indicate that the sense of effort is related to increased muscle activation[8,9] and shows a linear increase as increased load is placed on respiratory,[10] lingual,[11] or vocal[12] muscles. Taken together, these studies indicate that variations in sense of effort are directly associated with physiological changes in performance of a motor task such as speech.

Hyperfunctional voice can be differentiated from normal voice by using noninvasive aerodynamic measures.[13] Aerodynamic measures such as translaryngeal airflow, subglottal pressure, and translaryngeal resistance provide direct indicators of laryngeal physiology and can differentiate abnormal from normal voicing patterns.[13,14] When phonation is produced with increased constriction of the vocal folds and surrounding regions, airflow through the vocal folds is reduced, subglottal pressure is increased, and translaryngeal resistance is increased relative to phonation produced during normal voice without undue

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constriction. Additional measures derived from the airflow signal can provide more precise information about vibratory patterns. Maximum flow declination rate (MFDR) reflects the speed at which the airflow decreases in the closing phase of vocal fold vibration and is associated with how rapidly the vocal folds are closing. Greater amplitude of vibration is associated with faster vocal fold closure, which may produce an increase in vocal fold collision forces. In a theoretical framework of vocal hyperfunction, Hillman et al[13,14] have proposed that distinct laryngeal configuration patterns differentiate patients with adducted versus nonadducted types of vocal hyperfunction. Data from small subgroups of voice-disordered patients showed that in people with adducted hyperfunction, decreased glottal airflow, increased subglottal pressure, and high MFDRs were evidenced in comparison with other voice disorder subtypes, factors that may predispose these individuals to vocal fold damage.[13,14]

Voice quality differences along the continuum of breathy to pressed reflect changes in laryngeal adduction. Peterson et al[15] studied the effects of systematic variation in voice quality on aerodynamic and laryngeal configuration measures. Pressed voice quality showed significantly higher ratings of laryngeal adduction than the other voice quality types, and breathy voice quality showed significantly lower ratings of adduction than either resonant or normal voice quality. Electroglottography measures significantly differentiated the voice quality types, with aerodynamic measures such as MFDR showing differential trends that were not statistically significant. Lack of differentiation of voice quality types by aerodynamic measures may have been impacted by low power associated with small sample size (seven participants). In contrast to the the study by Peterson et al, Grillo and Verdolini[16] found that the aerodynamic measure of translaryngeal resistance provided a sensitive indicator of the phonatory function differences that occur with varying voice qualities. In a study of 13 women with vocal expertise and normal voice, the researchers found that translaryngeal resistance reliably distinguished between a pressed, normal, and breathy voice.

In people with voice disorders, aerodynamic measures can be strongly associated with external ratings of voice quality, including breathiness and strain. Netsell et al[17] determined the relationship between subglottal air pressure and laryngeal airflow in 18 participants with mixed voice disorders and 30 normal speakers to gain insight regarding laryngeal dysfunction. Results indicated that participants with normal subglottal pressure and high glottal airflow were consistently rated by external listeners as having a breathy voice quality, whereas those with high subglottal air pressure and low airflow values were perceived to have a strained voice quality. Netsell et al hypothesized that patterns of high airflow, normal subglottic pressure, and perceived breathiness were associated with insufficient vocal fold adduction, whereas those of increased subglottic pressure, decreased glottal airflow, and perceived strain were indicative of hyperadducted vocal folds. These authors also suggested that some participants with voice disorders compensate for reduced vocal fold adduction by increasing subglottic pressure, which produces increased airflow and perceived roughness in voice quality.

Changes in the acoustic features of the speech waveform can also be associated with physiological changes in vibratory behavior of the vocal folds and are often related to aerodynamic changes. Rapid variations in subglottic pressure occur during vibration onset and offset,[18] and strong relationships between subglottic pressure and intensity are evidenced during consonant-vowel sequences when intensity level is varied.[19] Acoustic analysis in voice disorders has moved toward the use of spectral- and cepstral-based measures, which are derived from the spectral distribution of sound energy and do not rely on a time-based analysis of the acoustic waveform. Performing a Fourier-transform on the spectrum produces the cepstrum, which demonstrates peaks of harmonic energy in the signal. Cepstral peak prominence (CPP) indicates the degree to which the dominant energy peak (often attributed to the fundamental frequency [F_0]) is distinguished from the background noise level of the overall signal. Current research shows that CPP and the standard deviation (SD) of CPP are some of the strongest predictors of auditory-perceptual voice severity[20–23] and provide excellent discrimination of normal versus dysphonic voice.[20,24] The strong relationships that various acoustic measures show with aerodynamic and perceptual features of voice support the use of acoustic measures to reflect the underlying vocal behavior and indicate that both aerodynamic and acoustic measures are essential to consider when studying the physiological bases for effortful voice production.

To understand the physiology that contributes to vocal effort and strained voice quality, it is important to systematically vary the degree of vocal effort during speech and determine the aerodynamic and acoustic consequences. Determining the physiological variables that are predominantly used by healthy individuals when increasing their degree of vocal effort may improve our clinical understanding of which physiological variables are crucial to target in voice therapy to decrease the level of speaking effort in people with voice disorders. Individuals with voice disorders are unable to produce varying levels of vocal effort or strain before therapeutic intervention. In contrast, healthy adults without voice disorders can be trained to produce varying levels of vocal effort[12] and can reliably rate that level of effort.[25,26] Therefore, the present study determined the aerodynamic and acoustic features of vocal effort in normal speakers. The following study questions were addressed: (1) When producing speech with increased or decreased levels of vocal effort as compared with comfortable vocal effort, how do healthy adults alter their phonatory physiology? (2) What are the acoustic manifestations of these changes in phonatory function that occur with high vocal effort? and (3) Which aerodynamic or acoustic variables are the primary factors that are associated with an increase in vocal effort?

METHOD

Participants

This study was approved by the Institutional Review Board (IRB) at Syracuse University, and all participants provided informed consent and were paid for their participation.