The Impact of Vocal Hyperfunction on Relative Fundamental Frequency During Voicing Offset and Onset

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Purpose: This study tested the hypothesis that individuals with vocal hyperfunction would show decreases in relative fundamental frequency (RFF) surrounding a voiceless consonant.

Method: This retrospective study of 2 clinical databases used speech samples from 15 control participants and women with hyperfunction-related voice disorders: 82 prior to treatment (muscle tension dysphonia, *n* = 22; vocal fold nodules, *n* = 30; vocal fold polyps, *N* = 30) and 18 before and after surgical removal of vocal fold nodules or polyps. Acoustic samples were analyzed with respect to the RFF at the offset and onset of voicing surrounding a voiceless consonant.

Results: Individuals with vocal hyperfunction in a large clinical sample showed significant lowering of offset and onset RFF compared with controls. Voicing offset and onset RFFs were not significantly changed by the removal of vocal fold lesions in the surgical group.

Conclusions: Altered offset and onset RFF in patients with hyperfunction-related voice disorders can be interpreted as a by-product of heightened levels of laryngeal muscle tension. Measurement of RFF during voice offset and onset has potential for use as a simple, noninvasive measure of vocal hyperfunction.

KEY WORDS: vocal hyperfunction, muscle tension dysphonia, vocal nodules, vocal polyps, acoustic measures, fundamental frequency

Vocal hyperfunction is often implicated in many common voice disorders (Hillman, Holmberg, Perkell, Walsh, & Vaughan, 1989). It has been defined as "conditions of abuse and/or misuse of the vocal mechanism due to excessive and/or 'imbalanced' muscular forces" (Hillman et al., 1989, p. 373), characterized by excessive laryngeal and paralaryngeal tension (Aronson, 1980; Dworkin, Meleca, & Abkarian, 2000; Koufman & Blalock, 1991; Morrison, Rammage, Belisle, Pullan, & Nichol, 1983; Roy, Ford, & Bless, 1996). In some cases, vocal hyperfunction may lead to organic changes to the surface of the vocal fold such as nodules or polyps. When vocal hyperfunction produces dysphonia without any other known cause of the voice disorder (e.g., nodules or polyps), it is referred to as *muscle tension dysphonia* (MTD).

Current clinical practice relies primarily upon the subjective interpretation of patient history and physical examination to assess vocal hyperfunction. So even though hyperfunction is an important concept in the diagnosis and management of many common voice disorders, there is currently no established objective measure for detecting its presence or severity. The availability of methods for quantifying vocal hyperfunction would improve the clinical capability to more accurately diagnose and monitor the treatment of hyperfunction-related voice disorders. This study explored the use of short-term variations in fundamental frequency surrounding voiceless obstruent production as a possible noninvasive, objective measure of vocal hyperfunction.

Fundamental frequency of voicing depends on the rate of the vibration of the vocal folds, which is, in turn, dependent on the length, mass, and tension of the folds (Van Den Berg, 1958). For this reason, variation in fundamental frequency has long been associated with changes in underlying laryngeal muscle tension. However, average-speaking fundamental frequencies vary considerably among healthy speakers as well as throughout utterances of individuals due to intentional prosodic changes (Atkinson, 1976). As a result, relative changes on smaller time scales may be more useful in correlating fundamental frequency with the predominating background level of laryngeal muscle tension, as these are least likely to be the product of intentional control.

Although variations in fundamental frequency are also affected by the use of subglottal pressure (e.g., Titze, 1989), it is thought that fundamental frequency variability at the phonemic level is a result of laryngeal regulation associated with phoneme production (e.g., Löfqvist, 1995), with the cricothyroid (CT) muscle acting as the primary mechanism for raising pitch (e.g., Roubeau, Chevrie-Muller, & Lacau Saint Guily, 1997). House and Fairbanks (1953) observed that vowels following voiceless consonants showed consistently higher fundamental frequencies than those following voiced consonants. Stevens (1977) believed that such increases in fundamental frequency were the result of increases in vocal fold tension used to inhibit vibration during voiceless consonant production and that this tension carries over into the first few cycles of the following vowel. This view is supported by the work of Löfqvist, Baer, McGarr, and Story (1989), who found in three healthy speakers that the CT is particularly active during vocal onset. The authors argue convincingly that the vocal folds experience increased longitudinal tension during voiceless obstruents, which is reflected as an increase in fundamental frequency at the beginning of the vowel following a voiceless obstruent relative to the middle of the vowel. However, it should be noted that Ludlow, Sedory, and Fujita (1991), in their examination of another three healthy speakers, found conflicting results in which CT activity was not correlated with phonetic devoicing.

Characteristic patterns have been identified in the relative fundamental frequency (RFF) surrounding voiceless consonants. Ohde (1984) found that speakers had the highest fundamental frequency during the first few vocal cycles of vowel onset after voiceless stop consonant production, a pattern that did not appear during production of voiced stop consonants. In an examination of RFF surrounding a voiceless consonant, Watson (1998) found that younger speakers (23–27 years of age) had relatively stable fundamental frequency in the 10 cycles prior to devoicing, whereas older speakers (68–85 years of age) showed a drop in fundamental frequency. Watson used his findings in combination with those of Ohde (1984) and Fukui and Hirose (1983) as a basis for hypothesizing that RFF changes can be attributed to both laryngeal muscle tension and aerodynamics. Specifically, Watson postulated that vocal fold tension is increased just prior to voiceless consonant production, contributing to increases in RFF at the end of the preceding vowel. The tendency of speakers to begin abduction of the vocal folds in the vowel prior to devoicing (e.g., Fukui & Hirose, 1983) was hypothesized to effect a decrease in the RFF preceding devoicing. The interplay of these two mechanisms could lead to the relatively constant fundamental frequency that Watson observed in young speakers. Watson hypothesized that the higher RFF at the onset of voicing after the consonant is caused by a combination of both increased vocal fold tension and increased airflow rate that is carried over from the preceding consonant.

More recently, this phenomenon has been explored as a function of development (Robb & Smith, 2002) and in individuals with Parkinson's disease (PD; Goberman & Blomgren, 2008). An examination of individuals at 4, 8, and 21 years of age found no significant differences between the age groups (Robb & Smith, 2002); however, in the group of adults, the RFF in women was consistently higher than that found in men (Robb & Smith, 2002). Goberman and Blomgren (2008) found that individuals with PD showed lower RFF during both vocal offset and onset when compared with age-matched controls. Differences between participants with PD and controls were reduced when PD participants were in their medication ON state. One explanation for this finding is that individuals with PD are experiencing increased laryngeal muscle tension associated with overall rigidity, resulting in less relative changes in tension levels during the offset and onset of voicing. This interpretation is supported by the finding of Gallena, Smith, Zeffiro, and Ludlow (2001) that increased thyroarytenoid muscle activity in individuals with PD was correlated with perceptual measures of voice onset and offset impairment. However, although it seems reasonable to attribute the finding of altered RFF in PD patients to rigidity, it must be acknowledged that PD patients also display evidence of rigidity in the respiratory system (e.g., Solomon & Hixon, 1993). This could somewhat confound the existence of a straightforward relationship between laryngeal rigidity and alterations in RFF in PD patients, given Watson's (1998) assertion that onset and offset RFF characteristics are determined by a combination of aerodynamic factors and vocal fold tension. This suggests a possible role for the use of RFF as a marker of vocal hyperfunction, a condition characterized by increased levels of laryngeal muscle tension.

The purpose of this study was to determine offset and onset RFF surrounding a voiceless obstruent in patients with voice disorders that are associated with vocal hyperfunction. We hypothesized that the increased laryngeal muscle tension thought to be displayed in individuals with vocal hyperfunction would restrict the normal short-term variations in tension that occur before and after voiceless consonant production. The restricted variation in laryngeal muscle tension was expected to significantly alter the normal impact of voiceless consonant production on offset and onset RFF. Specifically, it was expected that patients with vocal hyperfunction would have less of a relative increase in laryngeal muscle tension prior to voiceless consonant production, which would be reflected in lowered offset RFF as compared with controls. The presence of vocal hyperfunction would also restrict the relative increase in laryngeal muscle tension that is typically carried over into the vowel following a voiceless consonant, which would cause a similar lowering of onset RFF as compared with controls. This hypothesis was specifically tested in Experiment 1. A second experiment was also performed that compared RFF before and after surgery to remove nodules or polyps. This was done to assess the impact on RFF of removing structural changes that are associated with vocal hyperfunction to ensure that effects on RFF associated with vocal hyperfunction were truly caused by behavior rather than structure. We hypothesized that these individuals would not have a change in RFF as a result of this surgical procedure, given our underlying hypothesis that the differences in RFF between individuals with voice disorder and controls are due to laryngeal muscle tension, which would not be expected to change in the immediate postsurgical period.

Experiment 1

Method

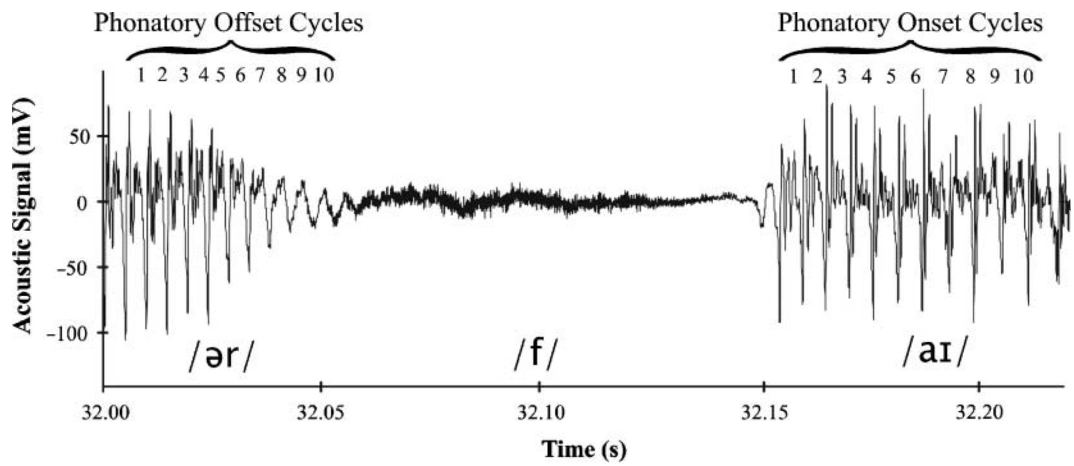
Participants. The acoustic recordings for this experiment came from healthy speakers and a group of patients with voice disorders. Participants were females at least 18 years or older. The control group consisted of 15 individuals with normal voice between the ages of 22 and 33 (M = 24.7 years, SD = 2.8). These participants were nonsmokers with no history of a speech, language, or hearing disorder.

The group of individuals with voice disorders was obtained from an archival de-identified database of voice samples collected by clinicians at the Massachusetts Eye and Ear Infirmary between 1992 and 2004 during routine clinical practice and consisted of 82 patients with voice disorders commonly associated with vocal hyperfunction prior to any treatment. The group with voice disorders was designed to represent the typical clinical realm of vocal hypefunction by including subjects with nodules and polyps and without MTD structural changes to the vocal folds. Diagnoses were made based on comprehensive voice evaluation procedures that included endoscopic, acoustic, aerodynamic, and perceptual assessment by a team consisting of a laryngologist and one or more certified speech-language pathologists. The database was screened to include females above the age of 18 years and to form three groups based on diagnoses of either MTD, true vocal fold nodules, or true vocal fold polyp. For each group, an attempt was made to randomly choose for inclusion 30 exams from separate individuals with equal numbers of singers and nonsingers. However, only 22 exams were available for inclusion in the MTD group, consisting of seven singers and 15 nonsingers. This effort to include equal samples of singers and nonsingers was based on the possibility that there were systematic differences between the manifestation of vocal hyperfunction in singers and nonsingers. Without specific effort to provide equal samples of singers and nonsingers, a random sample of the database would be likely to be overwhelmed with samples from singers due to the specialized nature of the voice clinic in which the samples were recorded. The average ages of the participants in the nodules, MTD, and polyps groups were 32.8 (SD = 13.0), 51.3 (SD = 18.5), and 37.2 (SD = 11.5), respectively.

Data recording and analysis. All acoustic recordings were made in a sound-treated room using a digital audio tape recorder (Tascam Model DA-30) or the Computerized Speech Lab (CSL; KayPentax) and a head-mounted condenser microphone (Sony ECM 50 or Sennheiser MK E2) with sampling rates of $\geq$25 kHz. Participants read the first paragraph of "The Rainbow Passage" (Fairbanks, 1960).

Time wave-forms of the samples were displayed in Praat acoustic analysis software (Boersma & Weenink, 2008), and the following word pairs were identified: "ever finds" and "looking for." These pairs were used to collect data from three voiced–voiceless–voiced combinations: "/ər/-/f/-/aɪ/," "/ʊ/-/k/-/ɪŋ/," and "/ɪŋ/-/f/-/ɔr/." The 10 periods of vibration prior to and after the voiceless consonant were measured using the pulse function in Praat (Boersma & Weenink, 2008). Instantaneous fundamental frequency was calculated as the inverse of each period. All frequencies were then converted to semitones (ST) relative to the points in the voicing furthest from the

Figure 1. Example of the acoustic waveform of an area of voice offset and onset used for analysis.



voiceless consonant (Cycle 1 in voicing offset and Cycle 10 in voicing onset; see Figure 1). In a subset of eight control participants, fundamental frequencies were studied across the three voiceless consonants measured using a two-factor analysis of variance (ANOVA), which did not find a statistically significant effect of the particular voiceless consonant. Therefore, for each participant, the fundamental frequency in ST was averaged across the voiceless consonants studied.

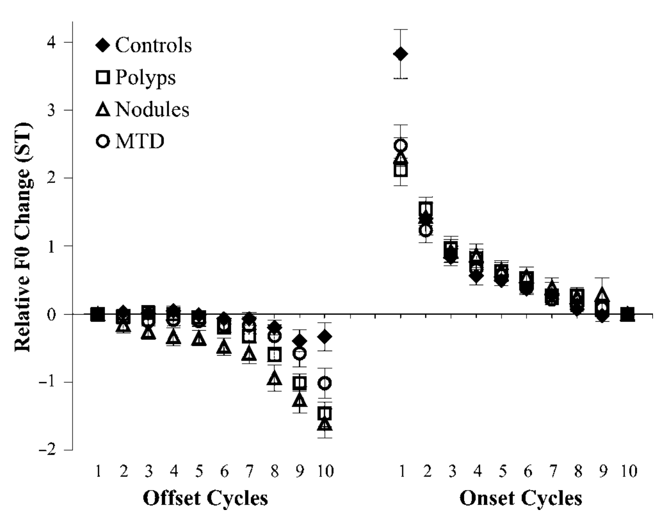
In order to assess inter- and intrarater reliability, approximately 10% of samples were independently analyzed by a second researcher and were re-evaluated (3 months later) by both researchers, yielding interrater reliability (as measured with Pearson's R of .97) and intrarater reliability for each researcher of .97.

Statistical analysis. In the individuals with voice disorders (nodules, MTD, polyps), a three-factor ANOVA was used to assess the effects of group, cycle, and the singer/nonsinger distinction. Two-factor ANOVAs were used to assess the effects of group (controls, nodules, MTD, and polyps) and cycle, followed by one-sided Dunnett simultaneous tests to assess the differences between controls and the three subcategories of individuals with voice disorders (nodules, MTD, and polyps). Two-sided Dunnett simultaneous tests were also performed between all RFF cycles and 0.

Results

A three-factor ANOVA on group, cycle, and the singer/nonsinger distinction in individuals with voice disorders did not find a significant effect of the singer/nonsinger distinction (p = .99). Thus, singer and nonsinger data were collapsed for further analyses. The RFF in ST that was found for controls (n = 15) is shown relative to individuals with vocal hyperfunction (N = 82) in Figure 2. A two-factor ANOVA found statistically significant effects of both group (controls, nodules, MTD, and polyps; $p < .001$), cycle ($p < .001$), and the interaction ($p < .001$). One-sided Dunnett simultaneous tests found statistically higher RFF values in controls (n = 15) when compared with each of the groups with voice disorder (nodules: n = 30, $p < .001$; MTD: n = 22, p = .014; polyps: n = 30, p = .002). Two-sided Dunnett simultaneous tests found statistically significant differences in RFF of offset Cycles 8–10 and onset Cycles 1–6 ($p < .05$), relative to 0.

Figure 2. Mean values of the relative fundamental frequency (RFF) change for control participants (n = 15) and participants with vocal hyperfunction from Experiment 1 by group: polyps (n = 30), nodules (n = 30), and muscle tension dysphonia (MTD; n = 22). Error bars show the standard error. ST = semitones.



Experiment 2

Method

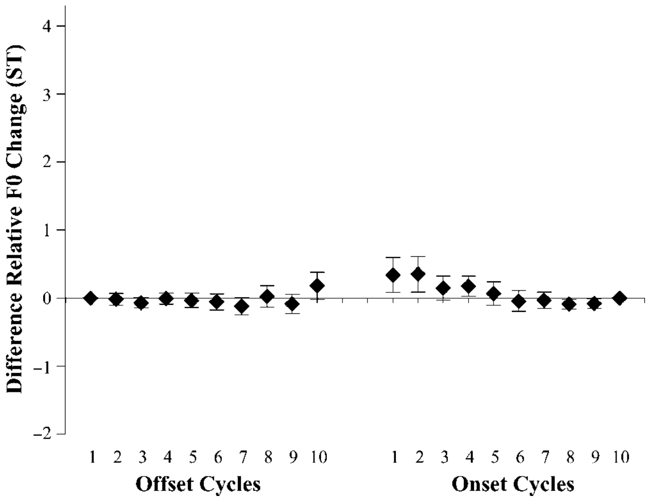
Participants. Based on the results of Experiment 1, pre-surgical and post-surgical data from individuals with nodules and polyps were used to further isolate the possible effects of structural changes in the vocal folds (vocal fold lesions) on RFF results for hyperfunctionally related voice disorders. De-identified data were obtained from an archival database of voice samples collected by clinicians at the Massachusetts General Hospital Center for Laryngeal Surgery and Voice Rehabilitation between 2004 and 2008 during routine clinical practice. The group consisted of 18 women 19–61 years of age (M = 39.2, SD = 11.2) who were diagnosed with vocal nodules or true vocal fold polyps and had recordings before and after surgery to remove their benign lesion(s). Diagnoses were made based on comprehensive voice evaluation procedures that included endoscopic, acoustic, aerodynamic, and perceptual assessment by a team that consisted of a laryngologist and one or more certified speech-language pathologists. Pre-surgical and post-surgical recordings were performed within 30 days, with no intervening voice therapy. The time between surgery and the postsurgical recording was at least 10 days and, in most cases, was approximately 14 days.

Data recording and analysis. Acoustic recordings were made in a sound-treated room using the CSL (KayPentax) and a head-mounted condenser microphone (Sony ECM 50 or Sennheiser MK E2) with sampling rates of 44 kHz. Participants read the first paragraph of "The Rainbow Passage" (Fairbanks, 1960), and time wave-forms of the samples were analyzed with Praat acoustic analysis software (Boersma & Weenink, 2008), as described in the Method section of Experiment 1. A one-sided, paired Student's t test was performed between pre-surgical and postsurgical samples. The one-sided test was chosen given our a priori hypothesis that postsurgical samples might show increased values of RFF. A power analysis showed that the 18 participants studied here were sufficient to find effect sizes such as those seen between controls and the individuals with nodules or polyps from Experiment 1: α = .05, power = 75%.

Results

Comparison of the RFF between pre-surgical and post-surgical (n = 18) recordings using a paired Student's t test did not yield any statistically significant differences (one-sided, p = .16). Figure 3 shows the differences (post – pre) between pre-surgical and post-surgical recordings.

Figure 3. Mean differences (post – pre) of the RFF change of individuals with nodules and polyps in Experiment 2 (n = 18). Error bars show the standard error.



Discussion

The offset and onset RFF values seen in these healthy controls in Experiment 1 are consistent with previous work in young healthy controls, particularly the work of Robb and Smith (2002). In 21-year-old individuals, they saw generally small changes in offset (<1 ST) and a larger change in the first cycle of onset (around 3 ST). Although these results are also similar to the work of Watson (1998), he observed mostly positive offset RFF (0.50–1 ST) in younger people (23–27 years of age), whereas our offset values were slightly lower. All types of patients with vocal hyperfunction (nodules, MTD, and polyps) studied in Experiment 1 showed lowered short-term RFF values compared with controls (see Figure 2). One possible interpretation of this finding is that there is a decrease in the effects of phonetically mediated vocal fold tension due to increased overall levels of laryngeal muscle tension in individuals with vocal hyperfunction.

Although there was a significant main effect of group on RFF, there was also a significant Group × Cycle interaction, indicating a difference in RFF between groups on some cycles but not others. Further, Dunnett simultaneous tests found statistically significant differences in RFF of offset Cycles 8–10 and onset Cycles 1–6, relative to 0. This is likely a result of the nature of the RFF measurement. The frequency at each cycle is converted to ST relative to the points in the voicing furthest from the voiceless consonant (Cycle 1 in voicing offset and Cycle 10 in voicing onset). This procedure is meant to normalize possible changes in the fundamental frequency to that at a "steady state" location within the vowel, and it has the added effect of setting conditions on the main effect of group on RFF.

The pre-surgical and post-surgical recordings in Experiment 2 were studied to examine whether the removal of the lesion resulted in normalization of the RFF during voicing offset and onset so as to determine whether the effects in RFF seen in Experiment 1 were not solely a result of increased overall laryngeal muscle tension but were also contributed to by the presence of the vocal fold lesions in individuals with nodules or polyps. Our results indicate that the mere presence of pathology does not affect the voicing offset and onset RFF because no difference was seen in RFF between pre-surgical and post-surgical data. These findings are interpreted as showing a postsurgical persistence of habituated hyperfunctional behaviors prior to any voice retraining (voice therapy; e.g., Su, Hsiao, & Hung, 2007). Similar conclusions have been reached previously based on aerodynamic studies in patients surgically treated for benign vocal fold lesions (Hillman et al., 1989). Taken together, such results lend general support to the view that these patients would benefit from postsurgical vocal retraining (voice therapy) to reduce persistent hyperfunction and thereby diminish the potential for the recurrence of pathology.

A possible factor in the interpretation of our results is the effect of age on the RFF. Watson (1998) found differences between younger speakers (23–27 years of age) and older speakers (68–85 years of age) in the offset RFF, although not the onset RFF. The ages of the individuals examined in this study differ between the disordered groups and the control group, with the control group consisting of an overall younger set of voices. The disordered groups are not, however, in the range of the older speakers studied by Watson (1998), and it is not known how the age-related changes in RFF may develop between the two extremes explored in that study. Two aspects of the data collected in this study indicate that age effects are not the primary cause of the difference between the disordered groups and the control group. First, although the average age of individuals in the MTD group was greater than that of individuals with polyps and nodules (51.3 years vs. 37.2 and 32.8 years, respectively), they showed the least amount of offset RFF change potentially associated with older age. Second, although Watson (1998) did not see differences in onset RFF related to age, disordered individuals in the present study differed from controls in onset RFF, which cannot be attributed to an age difference.

In summary, the lowered RFF during offset and onset of voicing is likely the result of the consistent difference between controls and the individuals with voice disorders: greater overall laryngeal tension in individuals with vocal hyperfunction. The study by Goberman and Blomgren (2008) found similar differences between controls and individuals with PD, which they hypothesized could be a result of increased general laryngeal muscle tension or decreased airflow rates during production of the voiceless consonant due to respiratory rigidity. The results of our study are consistent with interpreting the results of Goberman and Blomgren (2008) as a result of increased laryngeal muscle tension.

Conclusions

Individuals with vocal hyperfunction in a large clinical sample showed lowered short-term RFF changes than controls; one interpretation of this finding is that there is a decrease in the effects of phonetically mediated tension due to increased overall laryngeal muscle tension in individuals with vocal hyperfunction. Measurement of RFF during voice offset and onset has potential for use as a simple noninvasive measure of laryngeal tension. Future work should be done to collect this measure in conjunction with other acoustic and aerodynamic (airflow, pressure, and laryngeal resistance) measures associated with vocal hyperfunction to determine whether they correlate. Further, future work should include monitoring changes in RFF pre-therapy and post-therapy to ascertain its effectiveness as an indicator of a change in vocal hyperfunction. Further understanding regarding the nature of this measure could be gained in future studies with more direct experimental control, using altered auditory feedback or mimickery of disordered (hyperfunctional) voice production in individuals with healthy normal voice.

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