Annals of Otology, Rhinology & Laryngology 122(3):169-176.

Acoustic Correlate of Vocal Effort in Spasmodic Dysphonia

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Objectives: This study characterized the relationship between relative fundamental frequency (RFF) and listeners' perceptions of vocal effort and overall spasmodic dysphonia severity in the voices of 19 individuals with adductor spasmodic dysphonia.

Methods: Twenty inexperienced listeners evaluated the vocal effort and overall severity of voices using visual analog scales. The squared correlation coefficients (R^2) between average vocal effort and overall severity and RFF measures were calculated as a function of the number of acoustic instances used for the RFF estimate (from 1 to 9, of a total of 9 voiced-voiceless-voiced instances).

Results: Increases in the number of acoustic instances used for the RFF average led to increases in the variance predicted by the RFF at the first cycle of voicing onset (onset RFF) in the perceptual measures; the use of 6 or more instances resulted in a stable estimate. The variance predicted by the onset RFF for vocal effort (R^2 range, 0.06 to 0.43) was higher than that for overall severity (R^2 range, 0.06 to 0.35). The offset RFF was not related to the perceptual measures, irrespective of the sample size.

Conclusions: This study indicates that onset RFF measures are related to perceived vocal effort in patients with adductor spasmodic dysphonia. These results have implications for measuring outcomes in this population.

Key Words: acoustic measure, fundamental frequency, vocal effort, voice.

INTRODUCTION

Adductor spasmodic dysphonia (ADSD) is an action-induced and task-specific focal dystonia of the larynx that is characterized by intermittent hyperadduction of the vocal folds.[1] This hyperadduction is often associated with concomitant phonatory and pitch breaks,[2] although the number and duration of these breaks is variable within the broad range of severity in this relatively rare clinical population.[3] In addition to the dystonic symptoms, ADSD often appears with concurrent compensatory vocal hyperfunction,[4] with increased effort to produce voice. Thus, the characteristic clinical impression of voice quality in patients with ADSD is "strained-strangled,"[5] and the use of auditory-perceptual scales shows that overall ADSD severity (OS) and strain (perceived effort) are the most salient and reliably judged auditory-perceptual dimensions.[6,7]

Previous work to identify acoustic correlates of the perception of vocal effort (VE) in patients with ADSD examined the "voice break factor" and the standard deviation of the fundamental frequency collected during a maximally sustained vowel /*a*/.[8] The standard deviation of the fundamental frequency showed a significant but moderate correlation with the perception of "strain-strangled quality" (r = 0.49). Further work is necessary to identify acoustic measures that strongly correlate with the perception of VE in patients with ADSD.

A number of reports indicate that relative fundamental frequency (RFF) is an acoustic measure that may be negatively associated with increased vocal tension[9-11] and may show promise as a correlate of VE in patients with ADSD. Past work has shown that other measures of frequency may differentiate patients with ADSD from controls,[3] as well as those with muscle tension dysphonia.[12] The RFF surrounding voiceless consonants has been defined as the fundamental frequency of the cycles immediately before and after the consonant, normalized by the "steady state" fundamental frequencies of the voicing before and after the consonant.[9] The RFF is normalized in semitones relative to the steady-state instantaneous fundamental frequency to allow the changes in fundamental frequency to be compared across individuals with differing resting fundamental frequencies. In healthy speakers, the vocal cycles immediately after voiceless consonant production

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Presented in part at the meeting of the Acoustical Society of America, Seattle, Washington, May 23-27, 2011.

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(vowel onset) show an increase in RFF relative to the steady state of the vowel following the consonant.[11,13-15] Likewise, the RFF immediately before the production of the voiceless consonant (vowel offset) also shows characteristic patterns. Young healthy speakers have a relatively stable RFF during vowel offset, whereas older healthy speakers show a slight decrease.[11,14,15] However, average offset and onset RFF values have been shown to be significantly decreased in individuals with vocal hyperfunction (speakers with muscle tension dysphonia, vocal nodules, or vocal polyps) in comparison to healthy controls.[9]

In contrast to those with vocal hyperfunction, we hypothesized a different outcome in RFF values for patients with ADSD. For example, because ADSD symptoms are provoked by adduction of the intrinsic laryngeal muscles during purposeful speech, onset RFF symptoms may be increased; in contrast, we expect that RFF offset may not be as sensitive a measure for pure ADSD symptoms (versus compensatory hyperfunction). Because RFF measures are calculated from instances of voiceless-voiced combinations, we anticipated that fewer symptoms might be detected with this type of measure.[16] Thus, to ensure adequacy of statistical power, the effect of sample size in estimating the RFF must be examined. Previous studies of RFF have estimated the RFF of each speaker on the basis of 1 to 6 instances of vowel offset and onset surrounding a voiceless consonant in connected speech.[9-11,14,15]

The goal of the current study was to characterize the relationship between RFF and perceived VE and OS in speakers with ADSD. We hypothesized that these speakers would show lower RFF values relative to the values seen previously in healthy speakers,[9] whether because of primary hyperadduction from ADSD or because of concurrent compensatory vocal hyperfunction. We further hypothesized that RFF values would be negatively correlated with listener ratings of VE and OS. Specifically, we hypothesized that measures of RFF onset would be particularly sensitive to ADSD symptoms and that correlations between onset RFF and perceptual measures would be strengthened as a function of the number of available RFF productions used to estimate the average RFF of each speaker.

METHODS

Participants. The 2 groups of participants included speakers with ADSD and inexperienced listeners. The participants were native English speakers and reported no other speech, language, or voice symptoms beyond ADSD. They passed hearing screening tests at 40 dB for the octave frequencies of 250 to 4,000 Hz and were paid for their participation. All procedures were approved by the University of Washington Human Subjects Committee.

The speakers were 19 adults (9 male, 10 female; mean age, 58.2 years; SD, 10.8 years) who had received a diagnosis of ADSD from a board-certified laryngologist and had been evaluated by a team of at least 2 experienced speech-language pathologists. Diagnoses were based on case history, auditory-perceptual assessment of voice, videolaryngostroboscopy, and fine-wire laryngeal electromyography. The individuals had received multiple injections of botulinum toxin to treat their ADSD symptoms and had achieved reduction in voice symptoms after these injections. The speakers were recruited from a clinic at the University of Washington Medical Center and were recorded at the end of their treatment cycle immediately before injection of botulinum toxin as part of a previous study.[17] The average time since ADSD diagnosis for the speakers was 8.9 years (SD, 5.2 years). We deliberately selected the speakers to represent voice severities across the continuum.

The listeners were 20 healthy individuals (3 male, 17 female; mean age, 25.7 years; SD, 4.8 years) with no prior experience with or exposure to voice disorders. These individuals were recruited from the student population and broader community of the University of Washington.

Speech Collection and Stimulus Preparation. All speakers provided speech samples of the first paragraph of the Rainbow Passage[18] and a sentence loaded with voiceless consonants,[19] which were recorded with a headset microphone routed to a digital audiotape recorder at a sampling rate of 44.1 kHz in a quiet environment with low levels of ambient noise. The voiceless consonant–loaded sentence was used to ensure an adequate sampling of vocal behaviors for the acoustic analyses, given that previous work has shown differences in phonatory break frequency as a function of voiced versus unvoiced consonant composition.[16]

The speech samples were then transferred from digital audiotape to a desktop computer and stored as wav files. For the listener protocol, the second sentence of the Rainbow Passage (a mixed voiced and voiceless sentence) was extracted, and the intensity of each speech sample was normalized for peak energy with sound-editing software. This sample was chosen for the perceptual protocol so that the results could be compared with those of previous studies,[17,20] and because a previous study[16] showed that voice symptoms evoked by the Rainbow Passage were relatively equivalent to sentences loaded

RELATIVE FUNDAMENTAL FREQUENCY PRODUCTIONS USED FOR ANALYSIS

Text	*Phonetic Transcription*
“he saw”	/e/ /s/ /ɔ/
“half a”	/æ/ /f/ /ə/, or /æ/ /f/ /eɪ/
“a shape”	/ə/ /ʃ/ /eɪ/, or /eɪ/ /ʃ/ /eɪ/
“cross a”	/ɔ/ /s/ /ə/, or /ɔ/ /s/ /eɪ/
“a path”	/ə/ /p/ /æ/, or /eɪ/ /p/ /æ/
“path about”	/æ/ /θ/ /ə/
“or sixty”	/ɔr/ /s/ /ɪ/
“sister Kathy”	/ər/ /k/ /æ/
“Kathy”	/æ/ /θ/ /i/

with voiceless consonants. The samples were then entered into a custom-made software program that randomly generates speaker order, presents rating scales, and records responses. For assessment of intrarater reliability, approximately 25% of the samples were randomly repeated for each dimension (OS and perceived VE).

Acoustic Data Analysis. A total of 9 voiced-voiceless-voiced combinations (RFF productions) were selected for analysis from the voiceless consonant–loaded sentence “He saw half a shape mystically cross a path about 50 or 60 steps from his sister Kathy's house”[19] and are shown in the Table. A single investigator (C.E.S.) performed acoustic analysis on each RFF production by displaying the time waveforms of the samples in Praat acoustic analysis software[21] and using the pulse function to measure 10 periods of vibration before (offset) and after (onset) the voiceless consonant (Fig 1). The instantaneous fundamental frequency was calculated as the inverse of each period, T, and all frequencies were then converted to semitones relative to the points in the voicing furthest from the voiceless consonant. Thus, the instantaneous frequencies during offset were referenced to the first cycle (offset cycle 1), and the instantaneous frequencies during onset were referenced to the final cycle (onset cycle 10).

In our previous work, all available RFF productions for a single speaker were averaged to provide a more stable estimate of RFF than would be achieved with a single production.[9,10] In order to study the effects of the number of available RFF productions, averaging for each speaker was completed iteratively with 1 to 9 of the 9 available samples. For each speaker, the order of inclusion for productions was randomized. When glottalization or a lack of periodicity before or after the voiceless consonant production prevented us from reliably determining the RFF for a production, the RFF values from that production were excluded and only the remaining productions contributed to that average.

To assess intrarater reliability, 1 investigator (C.E.S.) reevaluated approximately 10% of samples approximately 18 months after the initial evaluation (Pearson's $r = 0.93$); the average difference for all RFF values in this sample was 0.04 semitones. To assess interrater reliability, a second trained researcher (L.B.; see Acknowledgments) analyzed approximately 10% of samples (Pearson's $r = 0.94$); the average difference for all RFF values between the 2 raters in this sample was 0.09 semitones.

Listening Procedures. Before performing the listening tasks, the listeners were provided definitions of OS and perceived VE and were familiarized with 100-mm visual analog scales. Overall severity was defined as “a comprehensive measure of how ‘good’ or ‘poor’ the voice sample is judged to be by the listener,”[22(p3017)] and VE was defined as “the perceived effort during phonation.”[23(1001)] The listeners first heard 2 speech samples of OS and VE — those of 1 male speaker with ADSD and 1 female speaker with ADSD who represented the approximate midpoint on the visual analog scale for OS or VE — to familiarize them with each auditory-perceptual dimension. These samples were chosen from an archived research database of speakers with ADSD that had been diagnosed in a manner similar to that of the speakers included in this study. The samples were selected by consensus judgments of 3 indepen-

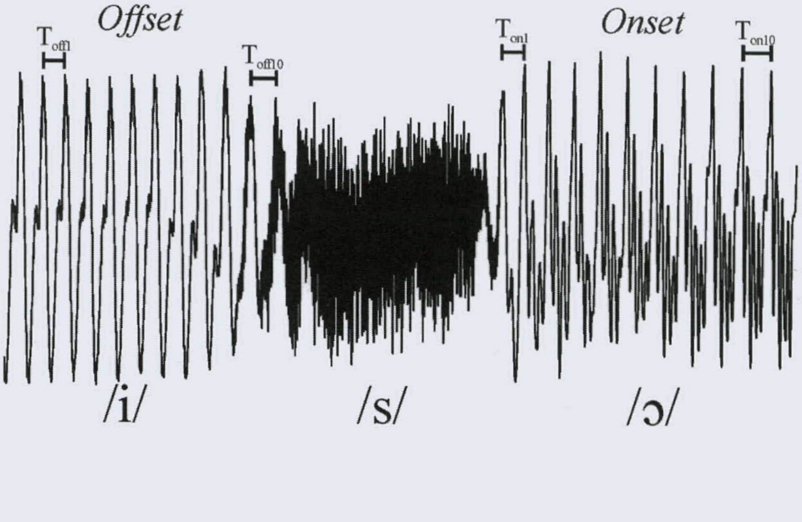

Fig 1. Example of relative fundamental frequency (RFF) production from text “he saw.”

dent raters to represent the approximate midpoints for each dimension (OS and VE), and they included the second sentence of the Rainbow Passage.

The listeners were then asked to make judgments of OS and VE for each speaker using a 100-mm visual analog scale. Stimuli were presented to the listeners at comfortable loudness levels through headphones. For each dimension, the listeners made judgments after a single presentation of each stimulus. The order of the perceptual dimensions (OS and VE) was counterbalanced, and speaker order was randomized across listeners. The entire listening session lasted approximately 25 minutes.

After data collection was complete, group means of listener ratings for OS and VE were calculated for each speaker. The listeners demonstrated adequate reliability; the mean Pearson product moment correlations between original and repeated samples were 0.91 (SD, 0.08) for VE and 0.71 (SD, 0.34) for OS. Interrater reliability was analyzed with Cronbach's α, which was 0.98 for both OS and VE.

Statistical Analysis. All statistical analyses were completed with Minitab statistical software (State College, Pennsylvania). To determine the strength of relationships between perceptual and RFF parameters, we calculated coefficients of determination (R^2) to predict the variance in mean perceptual scores for each speaker from 2 RFF parameters: RFF at offset cycle 10 and RFF at onset cycle 1. These 2 measures were selected as being most likely to differentiate among levels of vocal hyperfunction, given the patterns seen previously in this population,[9,10] and because they were the points furthest from those used for normalization (offset cycle 1 and onset cycle 10). For visualization of all RFF cycles, voices were grouped by VE severity such that "mild" was associated with VE scores from 4 to 30 mm (6 voices), "moderate" from 42 to 66 mm (9 voices), and "severe" from 75 to 95 (4 voices) on a 100-mm visual analog scale based on the structure of the Consensus Auditory-Perceptual Evaluation of Voice (CAPE-V).[24]

RESULTS

The mean VE and OS ratings of the 19 speakers were 49.4 mm (SD, 25.0 mm) and 45.6 mm (SD, 22.2 mm), respectively. Figure 2 shows a plot of OS ratings as a function of VE ratings, indicating that the speakers represented a full range of OS and VE ratings. Overall severity was statistically significantly ($p < 0.001$) related to VE ($R^2 = 0.97$). Given the high level of linear association between OS and VE, our further analyses focused more extensively on VE than OS. The mean RFF values for the 19 speakers are plotted in Fig 3 with respect to the mean RFF values of 15 speakers with healthy voice studied by Stepp et al.[9] An analysis of variance comparing the data from the current study to the previously collected control data showed a statistically significant effect of both vocal cycle ($p < 0.001$; $F = 51.0$; $df = 19$) and group ($p = 0.001$; $F = 12.0$; $df = 1$), as well as a significant interaction between vocal cycle and VE grouping ($p = 0.004$; $F = 2.12$; $df = 19$). A post hoc Tukey's simultaneous test found a significant difference ($p < 0.001$) between the RFF of patients with ADSD in the current study

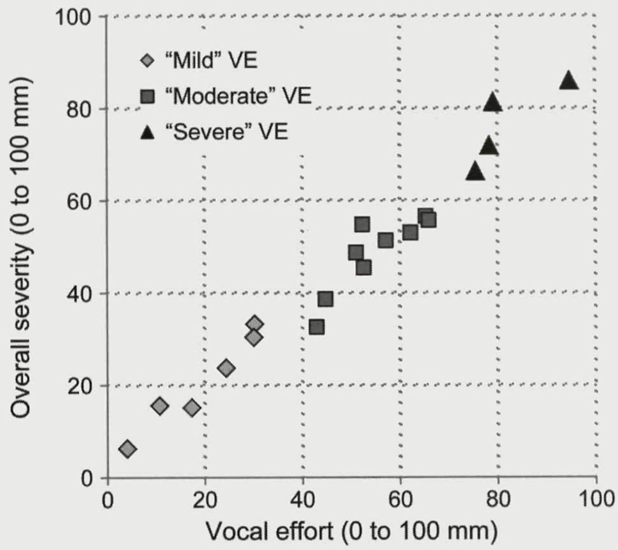

Fig 2. Overall severity ratings as function of vocal effort (VE) ratings in 3 participant groups.

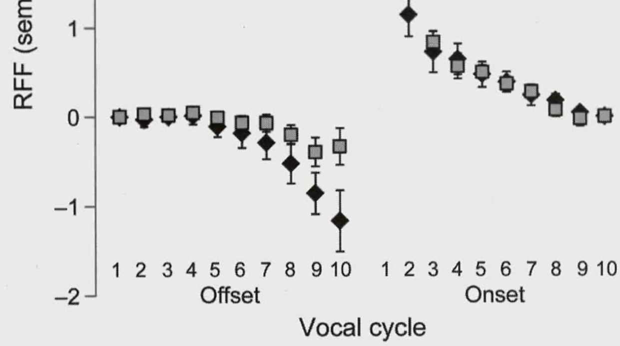

Fig 3. Mean values of RFF for all 19 participants with adductor spasmodic dysphonia (ADSD) in current study and for 15 control speakers with healthy voice. (Control data from Stepp et al.[9]) Error bars indicate standard error.

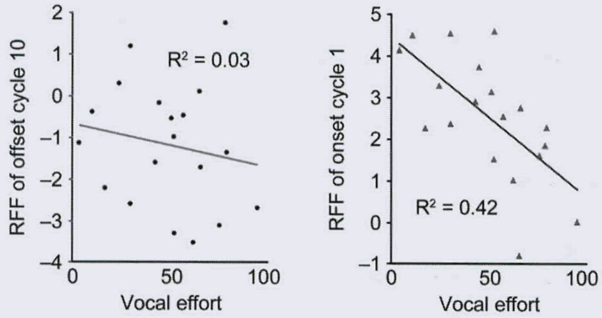

Fig 4. Mean values of RFF of onset cycle 1 and offset cycle 10 for each speaker as function of vocal effort.

and the RFF of individuals with healthy voice studied by Stepp et al.[9]

Figure 4 shows the RFF of offset cycle 10 and the RFF of onset cycle 1 based on all 9 RFF productions plotted as a function of VE. When all 9 RFF productions were used for the RFF, measures of the RFF of onset cycle 1 statistically significantly predicted VE ($p = 0.003$; $R^2 = 0.42$), but the RFF of offset cycle 10 did not significantly predict VE ($p > 0.05$; $R^2 = 0.03$). Likewise, the RFF of onset cycle 1 statistically significantly predicted OS ($p = 0.004$; $R^2 = 0.39$), but the RFF of offset cycle 10 did not significantly predict OS ($p > 0.05$; $R^2 = 0.02$). Figure 5 shows RFF data of participant groups based on VE for all RFF cycles. The mean RFFs of offset cycle 10 for the mild, moderate, and severe VE groups were –0.82 semitones (SD, 1.45), –1.32 semitones (SD, 1.33), and –1.34 semitones (SD, 2.20), respectively.

Figure 6 shows the effect of the number of available samples for RFF estimation on the coefficient of determination (R^2) between the RFF and the perceptual measures VE and OS. The strength of the relationships between the RFF of onset cycle 1 and the perceptual measures reach steady state (maximal values) when 6 or more samples are available for RFF estimation.

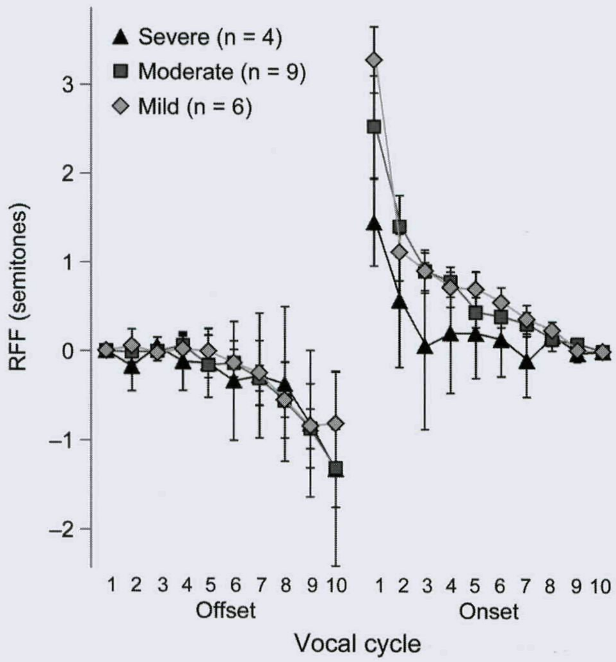

Fig 5. Mean values of RFF grouped by vocal effort ratings. Error bars indicate standard error.

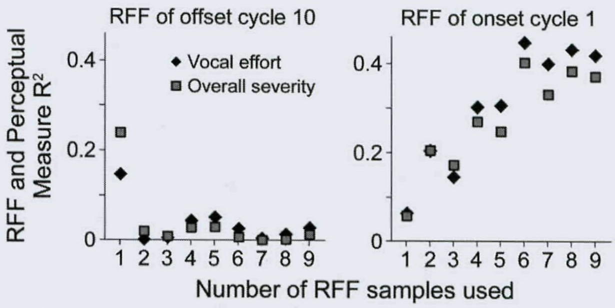

Fig 6. Correlation coefficients (R^2) between perceptual measures (vocal effort and overall severity) and RFF as function of available samples for RFF estimation.

DISCUSSION

The goal of this study was to characterize the relationship between RFF and perceived VE and OS in speakers with ADSD. Consistent with our original hypotheses, these speakers were found to have RFF values lower than those previously reported for healthy speakers,[9] and onset RFF values were negatively correlated with listener ratings of VE and OS. Also consistent with our original hypotheses, offset RFF values were not found to be sensitive to listener ratings of VE and OS. The relationship between the perceptual measures and onset RFF was strengthened as a function of the number of available RFF productions used to estimate the average RFF of each speaker.

Comparison to Literature. The mean RFF at offset cycle 10 in the 19 subjects was –1.2 semitones (SD, 1.5), and the mean RFF at onset cycle 1 was 2.6 semitones (SD, 1.5; Fig 2). These values are similar to those found by Stepp et al,[9] who studied women with hyperfunction-related voice disorders and reported mean RFF values of offset cycle 10 ranging from –1.017 to –1.61 semitones and mean RFF values of onset cycle 1 ranging from 2.12 to 2.48 semitones. The values seen in these 19 patients with ADSD are somewhat lower than those found in previous work in individuals with healthy voices, which showed a mean RFF of offset cycle 10 of –0.33 semitones and a mean RFF of onset cycle 1 of 3.82 semitones.[9] Before these results can be interpreted, they must be reconciled with perceptual results.

Correlations Between RFF and Perceptual Measures. When we used all 9 productions to compute the RFF estimates, 42% of the variance in perceived VE was significantly predicted by the RFF of onset cycle 1 ($p = 0.003$). Although the mean values of RFF of offset cycle 10 were generally higher in the subjects with ADSD than the values seen previously in controls, VE was not significantly predicted (3% of variance) by the RFF of offset cycle 10 ($p > 0.05$). Similar results were shown for OS, which was strongly related to VE ($R^2 = 0.97$). Although our work is limited by the relatively small number of speakers with ADSD, these speakers displayed a wide range of VE and OS such that associations between RFF measures and perceptual measures should be easily observable, if present. However, a potential limitation of the present study was that the speech sample used for acoustic analysis (a voiceless consonant–loaded sentence) differed from the speech sample used for perceptual ratings (second sentence of the Rainbow Passage). Despite this fact, we believe the use of different stimuli did not affect our results for two reasons. First, a strong association was found between the onset RFF and the perceptual measures. Second, a previous study[16] showed that voiceless consonant–loaded sentences evoked ADSD signs at a rate similar to that of the Rainbow Passage. Whether the phonetic context affects RFF in patients with ADSD should be a subject of future study.

Overall, the results of this study were consistent with our hypotheses on ADSD. In contrast to vocal hyperfunction, which is characterized by relatively sustained activation of the laryngeal and paralaryngeal muscles,[25] we expected speakers with ADSD to show different profiles for RFF at onset and offset. Specifically, we expected to observe increased perceptual symptoms with coinciding decreases in RFF at vowel *onset* for patients with ADSD, because their symptoms are provoked by adduction of the intrinsic laryngeal muscles. On the other hand, RFF at offset was not expected to be a sensitive measure for ADSD symptoms, because it involves abduction (ie, for production of the voiceless consonant); increases in this measure could be related to underlying compensatory hyperfunction. How these measures relate to the underlying physiology needs future study, but could be useful in characterizing the nature of ADSD and vocal hyperfunction.

We hypothesize that the relationship between the perception of VE and the RFF at onset may be linear. Previous work in individuals without voice disorders has shown the highest values of RFF at onset.[9] Further, in this population of individuals with ADSD, increases in VE were associated with concomitant reductions in RFF at onset. In contrast, the relationship between VE and RFF at offset appears to be nonlinear. The current results, in combination with our previous work,[9] suggest that the RFF at offset is significantly higher in healthy young adults than in individuals with voice disorders associated with vocal hyperfunction and ADSD; however, the individuals with ADSD studied here showed no evidence of a linear relationship in which small increases in the severity of the voice disorder resulted in small reductions in the RFF at onset. Rather, the relationship might best be described as a step function in which individuals with even perceptually mild voice disorders showed substantially lower RFF values.

RFF Estimate Quality Depends on Number of Samples. Previous studies have used manual estimation of RFF, with estimates averaged over 1 to 6 vowel–voiceless consonant–vowel instances produced in connected speech.[9-11,13-15] However, in the current study the RFF of onset cycle 1 was increasingly correlated with the perception of VE as more samples were used to compute the RFF estimate (Fig 6). These results were consistent with our expectations, based on the task specificity hypothesis for ADSD.[20] For example, Erickson[16] noted that voice symptoms and signs in speakers with ADSD varied with the phonetic context. Specifically, sentences loaded with all voiced consonants (b, d, g, z) provoked more frequent phonatory breaks than did sentences loaded with voiceless consonants (p, t, k, s). Because RFF measures are calculated from voiceless-voiced combinations, one might expect fewer symptoms to be detected in these types of stimuli.[16] In this case, estimates based on at least 6 samples were required to reach an "asymptotic" level of association between the RFF of onset cycle 1 and VE.

This finding is crucial to the future study of RFF and its potential clinical adoption. Currently, RFF is manually computed by a trained technician. Increasing the productions required for an estimate from 1 to 6 would increase the required computational time sixfold, creating a significant impediment to large-scale use of RFF. Our future studies will work to develop automated measures of RFF in order to facilitate its clinical study.

Models of RFF Production and Clinical Utility. Our previous work has shown that the RFF is lower relative to typical speakers in individuals with voice disorders associated with vocal hyperfunction,[9] and that after successful voice therapy, the RFF values of individuals with vocal hyperfunction normalize (increase) toward values seen in unimpaired speakers.[10] We previously postulated that RFF production is due to a confluence of aerodynamic, kinematic, and tension changes surrounding voiceless consonants and that an increase in baseline laryngeal tension might leave less "room" for tension-mediated changes in RFF. According to this theory, changes in baseline tension should affect offset and onset RFF values in the same manner. Although both offset and onset RFF values in the ADSD population examined in the current study showed a decrease relative to previous findings in healthy voices,[9] the onset RFF showed a quasi-linear decrease with increases in VE, whereas the offset RFF did not.

This difference could be a result of the hyperadduction associated with ADSD that is superimposed on baseline tension effects. In contrast, another interpretation is that this difference in offset and onset behaviors in relation to VE may be the result of nonlinearity in the relationship between laryngeal tension and RFF. Our future work is aimed at studying RFF production in concert with aerodynamics, vocal fold kinematics, and electromyographic measures in speakers with healthy voices, in speakers with voice disorders primarily associated with vocal hyperfunction, and in speakers with ADSD in order to carefully characterize these relationships.

In the current study, the RFF of onset cycle 1 was significantly correlated with listener ratings of VE, explaining up to 42% of the variance in VE in speakers with ADSD. This result is promising for the potential use of onset RFF as a marker of treatment success in ADSD (eg, examining the effects of botulinum toxin). Conversely, offset RFF is not sensitive to changes in the amount of VE, but does appear to be specifically associated with voice disorders in general.[9,26] These results are promising for the application of RFF as a diagnostic marker and as a measure of rehabilitation progress. However, our finding that estimates based on at least 6 samples are required to reach an "asymptotic" level of association between the RFF of onset cycle 1 and VE suggests that RFF cannot be clinically useful until automatic algorithms have been developed.

CONCLUSIONS

This study characterized the relationship between RFF and listeners' perceptions of VE and OS in the voices of 19 individuals with ADSD. Increases in the number of acoustic instances used for the RFF average led to increases in the correlation between the RFF at the first cycle of voicing onset (onset RFF) and the perceptual measures, with the use of 6 or more instances resulting in a stable estimate. When all data were used, the onset RFF predicted 42% of the variance in VE, whereas the offset RFF only predicted 3% of the variance in VE. Thus, onset RFF is correlated with perceived voice quality in patients with ADSD, and guidelines should be developed for calculating reliable estimates of RFF in future research.

Acknowledgments: The authors thank Leah Bowen for performing acoustic analysis for interrater reliability of relative fundamental frequency, and Devon Sawin for performing perceptual data analysis.

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