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Evaluation of auditory and visual feedback for airflow interruption

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Abstract

Introduction—Clinical application of mechanical interruption methods for measuring aerodynamic parameters has been hindered by relatively high intrasubject variability. To improve intrasubject reliability, we evaluated the effect of auditory and visual feedback on subject performance when measuring aerodynamic parameters with the airflow interrupter.

Methods—Eleven subjects performed four sets of ten trials with the airflow interrupter: no feedback (control); auditory feedback (tone matching subject's F_0 played over headphones); visual feedback (real-time feedback of sound pressure level, frequency, and airflow); and combined auditory and visual feedback. Task order was varied across subjects. The effect of each feedback method on mean and coefficient of variation (CV) of subglottal pressure (P_s), mean flow rate (MFR), and laryngeal airway resistance (R_L ; P_s/MFR) compared to control trials was determined using paired t-tests. Feedback methods were compared against each other using one-way repeated measures analysis of variance.

Results—Each feedback method significantly decreased the CV of R_L compared to control trials (auditory: $p=0.005$; visual: $p=0.008$; combined: $p<0.001$). Auditory ($p=0.011$) and combined feedback ($p=0.026$) also decreased the CV of MFR. Mean MFR was significantly higher during trials with visual feedback compared to auditory feedback.

Conclusions—Each feedback method improved intrasubject consistency when measuring R_L . Feedback appeared to have a greater effect on MFR than P_s . While there is no clear optimal feedback method, each is preferable to not providing any feedback during trials. Evaluating new methods of visual feedback to further improve MFR and thus R_L measurement would be valuable.

Keywords

airflow interruption; mechanical interruption; auditory feedback; visual feedback; subglottal pressure; aerodynamics

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INTRODUCTION

Laryngeal health is typically evaluated using primarily subjective measures, including perceptual analysis, visual inspection including videostroboscopy, and patient self-reports. Though perceptual analysis has value and can reveal insights into patient laryngeal health and function, it is imprecise and unreliable when evaluating therapeutic interventions or comparing across patients (1, 2). Additionally, videostroboscopy is inadequate when evaluating the aperiodic vibration characteristic of dysphonia (3, 4). There is a need for reliable, quantitative, and objective functional laryngeal assessment.

Aerodynamic assessment provides information on the inputs to voice production and can be used to describe normal and disordered voice production (5). Central to aerodynamic assessment is the measurement of subglottal pressure (P_s), a parameter valuable in isolation that is also required for determination of vocal efficiency, laryngeal airway resistance (R_L), phonation threshold pressure, and phonation threshold power. Aboras et al. measured a wide range of acoustic and aerodynamic parameters and found that P_s was the only parameter predictive of patients' self-perception of dysphonia (6). Routine clinical measurement of P_s , therefore, may be valuable.

While tracheal puncture (7) and transoral or transnasal passage of a pressure transducer into the trachea (8, 9) provide accurate measurements of P_s , they are not practical for routine measurement in a clinical environment. Three methods which have been used to measure P_s noninvasively include the semi-occluded vocal tract technique, labial interruption, and mechanical interruption. The semi-occluded vocal tract technique allows for a steady-state measurement of phonation threshold pressure that does not require valving by the lips or a mechanical shutter (10). Recent studies using this technique have recruited mostly singers and experienced voice users, as the method creates a different "feel of the voice", which may require training sessions for subjects less familiar with voice production (11). While this method certainly has promise, it is unknown how feasible the task is for the general population. Labial interruption was proposed by Smitheran and Hixon and measures intra-oral pressure after production of a labial plosive (12). Though subject-controlled labial interruption can produce accurate measurements of P_s , the technique can be difficult for untrained subjects to master (13). In a direct comparison of labial and mechanical interruption, trials performed with mechanical interruption displayed significantly lower coefficient of variation for R_L than labial interruption (14). Numerous variations of mechanical interruption have been proposed to measure laryngeal or pulmonary parameters of interest. Mead et al. measured resistance to pulmonary airflow during a 100 milliseconds interruption effected by a rotating metal fin (15). More relevant to this study, Bard presented balloon-controlled mechanical interruption for estimation of P_s and found a correlation between indirectly measured P_s in the oral cavity and directly measured P_s via cricothyroid membrane puncture (16). Jiang et al. refined the method to allow for measurement of phonation threshold pressure (17). This variation of mechanical airflow interruption has been applied successfully to the measurement of aerodynamic parameters in patients with vocal fold polyps and nodules (18), Parkinson's disease (19), and spasmodic dysphonia (20).

The clinical utility of airflow interruption is currently limited by intrasubject measurement variability; therefore, investigating methods of improving measurement precision is warranted. One potential way to improve measurement precision would be to use intra-trial feedback which can help subjects maintain constant frequency and sound pressure level across serial trials. Maintaining constant frequency and sound pressure level can be complicated by ambient noise created by the device, which may be distracting to subjects. Burnett et al. demonstrated that the response of subjects to changes in auditory feedback is variable, with some subjects altering fundamental frequency to oppose the frequency-shifted

feedback, while other subjects attempt to match the new frequency (21). Additionally, Sapir et al. reported that subjects have difficulty maintaining constant vowels in the presence of clicking sounds (22). To address these issues, we evaluated auditory feedback, or “auditory masking,” as a supplement to the traditional airflow interruption apparatus (23). A sample of subject phonation recorded prior to the trials with masking was played on a loop over headphones. This addition resulted in decreased intrasubject standard deviation when measuring P_s .

In addition to auditory feedback, visual feedback also merits consideration. Real-time visual feedback has been used successfully in multiple disciplines. Recently, Engeberg and Meek demonstrated the potential of visual feedback to aid upper limb amputees in determining the grip force applied by a prosthetic hand (24). Visual feedback has also been used to improve the gait of persons with gait disturbances (25). Pertinent to this study, real-time visual feedback has been used for numerous applications within the voice arena. Lancioni et al. used a portable real-time visual feedback device to reduce excessive vocal loudness in persons with cognitive deficits (26). Further, Howard et al. found that providing real-time feedback on frequency and vocal tract area had a positive impact on students during singing lessons (27). There is great potential for the use of visual feedback in other voice-related applications.

To improve aerodynamic measurement precision, we evaluated three types of feedback (auditory, visual, and combined auditory-visual) in eleven normal subjects during mechanical airflow interruption. We hypothesized that providing feedback would result in lower intrasubject variability for noninvasive measurements of P_s , mean flow rate (MFR), and derived R_L (P_s/MFR). The decreased variability observed in this study after adding feedback may represent a key step towards including aerodynamic assessment in routine voice evaluations.

MATERIALS AND METHODS

Experimental setup

The experimental apparatus (figure 1) is similar to that described in Jiang et al. (17). Notable changes include the addition of a Linear Pneumotachometer (Series 3813, Hans Rudolph, Inc., Kansas City, MO) and materials required for auditory and visual feedback. Also, a mouthpiece was used instead of a mask to eliminate potential variability associated with mask placement.

Airflow interruption uses a tube with a mouthpiece (Series 9063, Hans Rudolph, Inc.) on one end and an inflatable balloon valve (Series 9340, Hans Rudolph, Inc.) on the other. This balloon inflates during the trial to interrupt subject phonation for approximately 500 milliseconds. It takes approximately 84 milliseconds for the balloon to fully inflate, thus completely occluding the lumen of the device. Inflation of the balloon is controlled manually by the experimenter with a handheld switch; the time at which the experimenter inflates the balloon during the trial is varied to avoid any potential confounding effect of subject anticipation. Previous versions of the airflow interruption device used a PVC pipe to connect the mouthpiece and balloon valve; in this study, the PVC pipe was replaced by a Linear Pneumotachometer and Pneumotachometer Heater Control (Series 3850A, Hans Rudolph, Inc.) to increase the accuracy of airflow measurement. Pressure and airflow inside the Linear Pneumotachometer are measured using a pressure and flow transducer/Pneumotach Amplifier (Series 1110, Hans Rudolph, Inc.). The voltage outputs of the transducer are connected to a data acquisition system (model AT-MIO-16 series, National Instruments, Austin, TX). Data are then sent to a computer where customized LabVIEW

8.5.1 software provides numerical and graphical outputs. A nose clip (Series 9014, Hans Rudolph, Inc.) is used to prevent velopharyngeal leaking.

Feedback

Auditory feedback consisted of playing a tone corresponding to the subject's fundamental frequency over headphones. The token used for this was recorded during a sustained / α / at the beginning of the experiment; the same tone was used for all trials using auditory feedback. The subject was allowed to set the volume and was instructed to set it at a level which was loud but not uncomfortable. A customized computer program was written to estimate the fundamental frequency and measure the sound pressure level of the digitized acoustic signal. Center clipping and autocorrelation were used to estimate fundamental frequency (28). We hypothesized that performing trials while listening to a tone corresponding to their fundamental frequency may aid subjects in maintaining a consistent frequency across trials.

Visual feedback consisted of real-time displays of airflow, sound pressure level, and fundamental frequency (figure 2); all three parameters were integrated into one display with frequency on the x-axis, sound pressure level on the y-axis, and airflow denoted by color. Normal ranges for frequency were determined prior to the trials during a sustained / α / at a comfortable pitch and a sound pressure level of approximately 72 dB. The normal limits of frequency and sound pressure level were displayed on the graph as solid lines, creating a rectangle within which the subject tried to maintain his or her real-time data point throughout the trial. To generate normal ranges of frequency and airflow, the subject phonated a sustained / α / into the device for approximately five seconds. The program then calculated the average frequency and airflow during this time. A method similar to that presented by Winholtz and Titze was used to measure sound pressure level using the digitized acoustic signal (29). Calibration of this measurement was performed using a sound pressure level meter (Part No. 33-2055, RadioShack, Fort Worth, TX) as a reference. This device has a manufacturer-reported error of ± 2 dB at 114 dB. This degree of error is within our allowable range of 70 – 75 dB. The sound pressure level meter was placed approximately 18 inches from the end of the device on a table in front of the subject. The subject remained sitting in the same position during the entire experiment, ensuring the distance from the meter to the end of the device remained constant. The analog output signal from the meter was digitized and processed to compute a relative sound intensity level. Prior to experimental trials, a calibration offset was found using a reference signal and a reading from the sound pressure level meter's display. This coefficient allowed for the computation of sound pressure level during trials using the digitized analog output signal of the sound pressure level meter. The target sound pressure level for all subjects was 72 dB. As it can be difficult to maintain a sound pressure level of exactly 72 dB, deviation within the range of 70–75 dB was considered acceptable. This ensured that all trials were collected at approximately the same sound pressure level while avoiding inconvenience to the subject (and thus decreased feasibility when applied clinically) associated with requiring trials to be repeated due to an unacceptable sound pressure level. When the balloon valve is not inflated, the airflow interrupter is essentially a hollow tube; therefore, any potential effect of the device on measured sound pressure level is negligible. The vocal effort required to produce phonation at a sound pressure level of 70–75 dB is approximately the same with or without the device.

Acceptable frequency varied across subjects with an acceptable window of 15 Hz centered about the subject's fundamental frequency. Real-time information on airflow was provided on the visual feedback screen as the color of the lines marking acceptable frequency and sound pressure level. Red indicated airflow higher than reference, yellow indicated airflow lower than reference, and green indicated an acceptable airflow.

Subject testing

This study was conducted under the review of the Health Sciences Institutional Review Board of the University of Wisconsin-Madison. Eleven subjects (five males and six females; age: 21.3 ± 1.2 years) volunteered to participate from around the campus of the University of Wisconsin-Madison. Exclusion criteria included presence of a voice disorder or hearing loss (which would negate the effects of auditory feedback).

Each subject performed four sets of ten trials with the airflow interrupter: control (no feedback); auditory feedback; visual feedback; and combined auditory-visual feedback. Trials using feedback were performed according to the aforementioned specifications. Each task consisted of the subject producing a sustained /a/ for approximately 5–7 seconds, during which airflow was interrupted by a mechanical balloon valve for approximately 500 milliseconds. Prior to beginning the experiment, the experimenter briefly explained how the device worked and allowed the subject to perform 2–3 practice trials without feedback in order to become accustomed to the balloon interruption. Task order was varied across subjects to avoid any potential confounding effect of comfort level with the balloon interruption. All trials were performed at a sound pressure level of 70 – 75 dB, as measured with a sound pressure level meter placed approximately 18 inches from the end of the device on a table in front of the seated subject.

Data and statistical analyses

P_s , MFR, and R_L measurements were extracted from raw data traces using a customized program. P_s was recorded consistently at 150 milliseconds into the interruption (30). MFR was determined using a window where the average flow measurement is determined over the span of approximately 200 milliseconds. R_L was calculated by dividing P_s by MFR.

The mean and coefficient of variation (standard deviation divided by the mean) of P_s , MFR, and R_L (P_s/MFR) were calculated. Differences between control trials and each type of feedback (auditory, visual, combined auditory-visual) were evaluated using paired t-tests. Tests were two-tailed with a significance level of $\alpha=0.05$. The three feedback methods were also compared against each other using a one-way repeated measures analysis of variance (ANOVA). If a significant difference across feedback methods was found, follow-up pairwise comparisons were conducted using the Holm-Sidak method to correct the significance level. Nonparametric testing was employed if data did not meet the assumptions for parametric testing. SigmaPlot 11.0 software (Systat Software, Inc., Chicago, IL) was used for all analyses.

RESULTS

Summary data and results of statistical analysis are provided in table 1. Notably, each feedback method significantly decreased the coefficient of variation of R_L compared to control trials (auditory: $p=0.005$; visual: $p=0.008$; combined: $p<0.001$). Auditory ($p=0.011$) and combined feedback ($p=0.026$) also significantly decreased the coefficient of variation of MFR (figure 3). No method had an effect on the coefficient of variation of P_s . Mean P_s for trials with visual feedback was discernibly lower ($p=0.054$) compared to control trials; however, this difference did not reach statistical significance.

When comparing the feedback methods against each other, there was no difference in coefficient of variation for any of the three parameters. Each method significantly decreased intrasubject variability compared to control trials, but none demonstrated superiority over the other feedback methods. Comparing means across feedback methods revealed a significant ($p=0.027$) difference for P_s and near significant differences for MFR ($p=0.06$)

and R_L ($p=0.078$). Follow-up pairwise comparisons showed a significant difference ($p=0.017$) between auditory and visual feedback for MFR.

DISCUSSION

We presented and evaluated several feedback methods which can be used in conjunction with mechanical airflow interruption to increase intrasubject measurement precision. All methods worked fairly well, as demonstrated by significant decreases in the coefficient of variation for R_L (table 1). Coefficient of variation of MFR was also decreased, but only in trials with auditory or combined auditory-visual feedback. While this study evaluated measurement variability over ten trials recorded at a single data collection session, feedback is also expected to have a beneficial effect over multiple recording sessions. The feedback methods were designed to help subjects maintain constant fundamental frequency, sound pressure level, and airflow over the course of multiple trials. As these variables can affect measurement precision, providing aids to subjects that help keep the variables constant would be expected to decrease measurement variability across sessions as well as across trials within a session.

Similar to a previous study evaluating intrasubject reliability in labial and mechanical interruption (14), MFR measurement was more variable than P_s measurement. We attempted to address this issue by including flow as a component in our visual feedback display; however, an effect on the coefficient of variation of MFR was not observed. This may be due to the type of feedback presented. To present all three parameters of interest (fundamental frequency, sound pressure level, airflow) in one image, we used color-coded feedback to provide information on airflow. Modifying airflow is not intuitive for subjects unfamiliar with laryngeal physiology; as a result, subjects sometimes over-compensated by using an excessively breathy or pressed voice. Alternative methods of flow feedback will be evaluated in future studies, including using dual plots with one dedicated to visual feedback of vocal acoustics and the second dedicated to visual feedback of flow. This method was not selected for this study as we thought it may be difficult for subjects to focus on two images at once; further experiments will determine if this is actually the case. Alternatively, feedback on flow could be eliminated entirely. Providing visual feedback on vocal acoustics is still valuable and may be adequate to improve measurement precision. Several subjects provided unprompted support for this notion, saying they focused more on the target, which corresponds to vocal acoustics, than its color, which corresponds to airflow.

Regardless of the method of feedback employed, it is necessary to monitor sound pressure level during trials. This is particularly important during trials with auditory feedback. In the presence of noise (such as a tone played over headphones corresponding to the fundamental frequency of subject phonation), subjects may have a tendency to increase the volume of their speech, a phenomenon known as the Lombard effect (31). We controlled for this by giving subjects cues if they inadvertently increased their sound pressure level. Sound pressure level is related to P_s (32, 33), and measurement comparisons could be confounded if not recorded at the same sound pressure level.

This study has two main limitations. First, a relatively modest sample size was recruited. Data from eleven subjects displayed clear trends; however, recruiting a larger sample is warranted. Second, this study was conducted only in subjects with normal voices. While we have successfully applied mechanical airflow interruption to subjects with a wide range of disorders (18–20), it is not known if these subjects may benefit from auditory or visual feedback. This will be evaluated in future studies.

If these methods were applied to subjects with voice disorders, several modifications may need to be made. When providing auditory feedback, the presence of type III voice (34) may complicate estimation of fundamental frequency. In this study, we used a technique which repeatedly estimates the fundamental over consecutive windows of time. Depending on the size of the window, this technique can be used to track a moving fundamental frequency. This requires that the frequency of the signal within a window be relatively constant, although it may change significantly over the course of several windows. Such a signal would be aperiodic in a global sense but periodic in a local sense. Decreasing the window size may allow for application to even severely disordered voice. Multiple recordings may need to be made to ensure a tone appropriate for a given subject is played during trials with auditory feedback. If visual feedback were applied, the absolute sound pressure level may need to be decreased, particularly for patients with severe glottic insufficiency for whom producing a sound pressure level of 70 – 75 dB may be prohibitively difficult. In older subjects, the visual feedback screen could also be modified to facilitate visualization. Possible changes include increasing size or contrast. No specific changes would need to be made if applying the feedback methods to perform pre- and post-treatment assessments. While some treatments are expected to cause a change in fundamental frequency, the specific value of a subject's natural fundamental frequency is inconsequential. The utility of feedback is in helping a subject maintain that natural fundamental frequency within and across trials. In this study, we provided a range of 15 Hz centered about the subject's natural, comfortable fundamental frequency (i.e., subjects were not all required to phonate at the same predetermined frequency). Therefore, it does not matter if pre- and post-treatment fundamental frequencies are different. In both cases, feedback is provided to help subjects maintain their natural fundamental frequency within and across trials. Importantly, airflow interruption has already been applied to a range of voice disorders (18–20). The feedback methods described in this study will facilitate rather than complicate task completion. If a less obtrusive method for measuring aerodynamic parameters is desired, alternative techniques such as the semi-occluded vocal tract technique (10, 11) or incomplete airflow interruption (35) could be employed. Evaluating how visual or auditory feedback can be combined with these methods to increase measurement precision is warranted.

Even without feedback, subject performance was reasonably good. This provides support for mechanical interruption, as a key benefit is the ability to obtain accurate estimation without training. Average coefficient of variation of P_s was only 12%, and P_s estimation was unaffected by the presence of feedback. This finding is different compared to our previous study which found a significant difference in intrasubject standard deviation between trials with and without auditory feedback (23); slight differences in the methods are likely responsible. In our previous investigation on auditory masking, a pre-recorded sample of subject phonation was played on a loop over headphones. In this study, a tone corresponding to the fundamental frequency of subject phonation was used. More importantly, our previous study used manual analysis of P_s based on pressure plateaus. P_s measurement in this study was automated and estimated consistently at 150 milliseconds into the interruption according to a previously described method (30). This difference in analysis likely accounts for the absence of a significant decrease in coefficient of variation of P_s . While the coefficient of variation of P_s was not significantly affected by the presence of feedback, differences were observed for MFR measurement. Calculation of R_L requires both MFR and P_s ; changes in either P_s or MFR measurement variability will thus both affect R_L estimation. As R_L considers both pressure and flow and is more reflective of the physical properties of the larynx, it is superior to isolated measurements of P_s or MFR and noninvasive measurement of it via airflow interruption would be a useful clinical adjunct.

CONCLUSION

Auditory and visual cues are a useful addition to airflow interruption which can improve precision when noninvasively estimating laryngeal airway resistance. Interestingly, the effect of feedback was more pronounced on MFR than P_s . While no optimal feedback method was identified in this study, each was preferable to control trials in which no feedback was provided. New visual feedback methods, particularly those providing different graphical displays of real-time airflow measurement, should be investigated. As the feedback methods used in this study improved intrasubject reliability, adding them to the standard airflow interruption setup may facilitate inclusion of aerodynamic assessment as a component in routine functional voice evaluation.

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Figure 1.
Schematic of airflow interruption device.

Figure 2.

Visual feedback display. Sound pressure level (SPL) is displayed on the y-axis, with an acceptable range of 70 – 75 dB. Frequency is displayed on the x-axis, with an acceptable range of 15 Hz centered about the subject's fundamental frequency (here: approximately 240 Hz). Airflow is displayed as the color of the lines showing target frequency and SPL. In the top display, the subject is phonating with high SPL and airflow, but low frequency. In the middle display, the subject is phonating with appropriate SPL, frequency, and airflow. In the bottom display, the subject is phonating with appropriate frequency, but low SPL and airflow.

Figure 3.

Coefficients of variation for subglottal pressure (P_s), mean flow rate (MFR), and laryngeal airway resistance (R_L) across trials. All feedback methods resulted in decreased coefficient of variation for R_L ; auditory and combined feedback also resulted in decreased coefficient of variation for MFR. Error bars represent standard error of the mean.

Table 1

Summary data and results of statistical analyses. P-values in columns following each feedback method represent results of paired t-tests comparing individual feedback method with control trials. Analysis of variance (ANOVA) p-values represent results of comparisons across the three feedback methods.

	Control	Auditory	p-value	Visual	p-value	Combined	p-value	ANOVA p-value
CV P_s	0.12 ± 0.07	0.12 ± 0.04	0.891	0.13 ± 0.08	0.692	0.12 ± 0.05	0.853	0.836
CV MFR	0.24 ± 0.08	0.16 ± 0.07	0.011	0.19 ± 0.153	0.195	0.16 ± 0.08	0.026	0.712
CV R_L	0.29 ± 0.09	0.19 ± 0.07	0.005	0.19 ± 0.12	0.008	0.17 ± 0.06	<0.001	0.709
P_s (cmH ₂ O)	8.28 ± 2.87	8.24 ± 2.18	0.206	7.35 ± 2.18	0.054	7.54 ± 2.02	0.205	0.027
MFR (L/s)	0.198 ± 0.076	0.169 ± 0.049	0.098	0.204 ± 0.073	0.696	0.199 ± 0.1683	0.700	0.06
R_L (cmH ₂ O/L/s)	46.05 ± 10.86	52.41 ± 15.33	0.206	40.06 ± 15.64	0.083	51.98 ± 24.08	0.328	0.078

CV = coefficient of variation; P_s = subglottal pressure; MFR = mean flow rate; R_L = laryngeal airway resistance.