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Estimating Subglottal Pressure via Airflow Interruption with Auditory Masking

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Abstract

Objective—Current noninvasive measurement of subglottal pressure using airflow interruption often produces inconsistent results due to the elicitation of audio-laryngeal reflexes. Auditory feedback could be considered as a means of ensuring measurement accuracy and precision. The purpose of this study was to determine if auditory masking could be used with the airflow interruption system to improve intrasubject consistency.

Study Design—A prerecorded sample of subject phonation was played on a loop over headphones during the trials with auditory masking. This provided subjects with a target pitch and blocked out distracting ambient noise created by the airflow interrupter.

Methods—Subglottal pressure was noninvasively measured using the airflow interruption system. Thirty subjects, divided into two equal groups, performed ten trials without auditory masking and ten trials with auditory masking. Group one performed the normal trials first, followed by the trials with auditory masking. Group two performed the auditory masking trials first, followed by the normal trials.

Results—Intrasubject consistency was improved by adding auditory masking, resulting in a decrease in average intrasubject standard deviation from 0.93 ± 0.51 to 0.47 ± 0.22 cmH₂O ($p < .001$).

Conclusions—Auditory masking can be used effectively to combat audio-laryngeal reflexes and aid subjects in maintaining constant glottal configuration and frequency, thereby increasing intrasubject consistency when measuring subglottal pressure. By considering auditory feedback, a more reliable method of measurement was developed. This method could be employed by clinicians, as reliable, immediately available values of subglottal pressure are useful in evaluating laryngeal health and monitoring treatment progress.

Keywords

Subglottal pressure; airflow interruption; auditory masking; audio-laryngeal reflexes

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INTRODUCTION

It is difficult to obtain accurate, consistent data when testing subglottal pressure (P_s) in the clinical setting. Invasive methods that measure P_s directly by placing a pressure transducer in the trachea are accurate (1), but are not clinically feasible due to both time constraints and patient discomfort. Available noninvasive testing depends on a subject's ability to maintain constant glottal configuration, fundamental frequency, and effort throughout the test. This is difficult due to short-latency audio-laryngeal reflexes which play a role in controlling phonation. External sound stimulates the reflex, which manifests in a response by the intralaryngeal muscles (2,3). While these responses play a key role in the auditory feedback control of phonation (4), they are problematic when measuring P_s . Acoustic stimulation can cause increases in vocal intensity and vocal fold adductor activity (5), leading to a subsequent elevation in and inaccurate estimation of P_s (6).

Several promising methods have been developed to noninvasively measure P_s , but their clinical utility has been limited by a lack of consistency. Smitheran and Hixon interpolated translaryngeal pressure and airflow to determine laryngeal resistance during the repetition of plosive consonants followed by vowel sounds (7). A similar method was employed by Rothenberg, who measured P_s during vowel production after a plosive consonant as part of a study presenting the inverse-filtering technique used to derive the glottal waveform (8). While these methods have been used with success, they require subject training to ensure trials are conducted properly (9). An alternative to subject-controlled labial interruption is mechanical interruption. Numerous variations of this have been proposed to measure P_s and laryngeal or pulmonary resistance, including the use of a rotary solenoid-driven valve by Mead *et al.* (10). A metal fin rotated to interrupt airflow, producing a single interruption which lasted approximately 100 ms. A second method was presented by Clements *et al.* which used repetitive interruptions of airflow to estimate pulmonary resistance (11).

Airflow interruption was later employed by Bard, who found a correlation between indirectly measured subglottal pressure in the oral cavity and subglottal pressure directly obtained through a translaryngeal puncture (12). Building on this principle, Jiang *et al.* developed the airflow interruption system using a balloon valve (13). The device was validated using a simultaneous direct measurement in a tracheotomy patient with a normal larynx. Its clinical applicability, however, has been hindered by high intrasubject variability. Ambient noise created by the device can be distracting to subjects, eliciting audio-laryngeal reflexes which lead to changes in subject fundamental frequency and glottal configuration. In order to develop a reliable testing procedure, auditory feedback could be considered.

Elman showed that regulating human phonation is affected by changes in the fundamental frequency of auditory feedback (14). When subjects received auditory feedback with a fundamental frequency shifted by as much as 20% above or below their fundamental frequency, they involuntarily changed their fundamental frequency to match the auditory feedback. Though subjects were unable to detect frequency shifts of 10%, they still compensated for the change. Burnett *et al.* determined different subjects have different reactions to changes in auditory feedback. While some change their pitch to oppose frequency-shifted feedback, others change their pitch to match the altered feedback (15). There is a large intersubject variability in the pitch-shift reflex to altered auditory feedback. The pitch-shift reflex is a closed loop negative feedback reflex that occurs in response to a difference between intended and perceived pitch. It has an approximate latency of 100 ms (16). Changes in phonation due to changes in the intensity of auditory feedback have also been studied. The Lombard effect states that humans involuntarily increase their vocal intensity when speaking in the presence of noise (17). The sidetone-amplification effect

describes how a subject will unknowingly change his vocal intensity to compensate for intensity-altered feedback (18).

Changes in phonation frequency or vocal intensity are problematic when attempting to estimate subglottal pressure. The opening and closing of the balloon valve during airflow interruption causes multiple problems. First, it causes the frequency and intensity of subject phonation to change briefly. Sounds created by the balloon valve represent an increase in environmental noise which triggers the Lombard effect, causing a change in vocal intensity. Subjects inadvertently alter glottal configuration, thus leading to changes in, and an inaccurate estimation of, P_s . Second, the sound of the balloon valve opening and closing approximates a series of clicks, which can startle subjects. Sapir found that subjects were unable to maintain constant phonation in the presence of clicking sounds. The clicks were 1 ms in length and were presented at irregular intervals. The auditory stimulation caused subjects to inadvertently increase their fundamental frequency. This change occurred due to audio-laryngeal reflexes, occurring as quickly as 13 milliseconds after the stimulus (19).

This study uses auditory masking to combat involuntary audio-laryngeal reflexes in order to make it easier for the subject to maintain a constant glottal configuration. A previously recorded sample of each subject's phonation is played over headphones to "mask" laryngeal reflexes, blocking out ambient noise and providing a target pitch for subjects while testing. It is predicted that adding auditory masking will decrease intrasubject variability and lead to more consistent measurements of P_s . Untrained subjects often experience difficulty when attempting to maintain a constant glottal configuration during airflow interruption experiments. If auditory masking enables subjects to maintain a constant glottal configuration, which is required for accurate measurement of P_s , accuracy as well as consistency could be improved.

MATERIALS AND METHODS

Experimentation setup

The experimental design is identical to the setup described in Jiang *et al.*, 1999 with the exception of adding headphones and Microsoft Sound Recorder software used for auditory masking (figure 1). Also, a mouthpiece was used instead of a mask (figure 2) to eliminate potential variability associated with mask placement. Microsoft Sound Recorder is an audio recording program that has a sampling rate of 22.05 kHz and produces audio files in 8-bit uncompressed PCM format. Files were created only to provide subjects with a looped recording of their own phonation, not for acoustic analysis. Therefore, the program specifications were adequate. Airflow interruption uses a PVC pipe with a diameter of 1.905 cm and a length of 12 cm. At one end of the pipe is a mouthpiece (Series 9063, Hans Rudolph, Inc., Kansas City, MO) which is held in the subject's mouth. At the other end of the pipe is an inflatable balloon valve (Series 9340, Hans Rudolph, Inc.) which inflates to interrupt subject phonation for 500 milliseconds. The firing of the balloon valve is controlled manually with a handheld switch. Pressure is measured inside the pipe using a pressure transducer / pneumotach amplifier (Series 1110, Hans Rudolph, Inc.). The voltage output of the transducer is connected to a data acquisition system (model AT-MIO-16 series, National Instruments, Austin, TX). These data are then sent to a computer where customized LabVIEW 8.0 software provides numeric and graphical outputs. A nose clip (Series 9014, Hans Rudolph, Inc.) is used to prevent airflow through the nostrils.

Subject testing

Prior to testing, approval was received from the Institutional Review Board of the University of Wisconsin-Madison. Hearing disorders were listed as a criterion for exclusion and verbal

confirmation was given by all subjects to confirm they had normal hearing. Thirty subjects were chosen randomly from around the University of Wisconsin-Madison. No requirements concerning health (other than normal hearing) or demographics were made, as the experimental device is designed to work on all types of subjects. The subjects were divided into two groups, each with fifteen subjects. Each subject performed ten trials without and ten trials with auditory masking. Group one performed the set of auditory masking trials first, and group two performed the set of auditory masking trials after the normal trials. Dividing the subjects into two groups ensured that any change in intrasubject standard deviation could not be solely attributed to subject comfort level with the experiment. A trial consisted of the subject phonating /a/ into the mouthpiece. For the set of ten auditory masking trials, a five second recording of subject phonation was made using Microsoft Sound Recorder. A stable sample, approximately one second in length, was selected and played on a loop over headphones during the set of ten masking trials. Sample stability was determined based on the waveform of the audio sample.

Data analysis

Subglottal pressure graphs were obtained using customized LabVIEW 8.0 software. A plateau representing the equilibration of supraglottal pressure with subglottal pressure was determined and recorded as the subject's P_s (figure 3). If multiple plateaus were observed, the first plateau was selected to represent subject P_s . Any additional plateaus would have been caused by pressure equilibration at a different intraoral volume following a reflexive response to the testing procedure. A Mann-Whitney rank sum test was performed to determine if there was a statistically significant difference in the average intrasubject standard deviation between trials without and with auditory masking. The test was two-tailed and a significance level of 0.05 was used.

To confirm that a potential difference in mean intrasubject standard deviation was not due to one method having a higher mean value of P_s , a paired t-test was performed to determine if there was a significant difference in mean P_s between the two testing methods. The test was two-tailed and a significance level of 0.05 was used. A Kolmogorov-Smirnov test was used to confirm normality of the data.

RESULTS

Intrasubject consistency was improved in 27 of 30 subjects by adding auditory masking to the standard airflow interruption setup. A Mann-Whitney rank sum test yielded a p-value $< .001$, indicative of a statistically significant difference between mean standard deviation without (0.93 ± 0.51 cmH₂O) and with (0.47 ± 0.22 cmH₂O) masking (figure 4). Average subglottal pressure measurement for all subjects was 6.28 ± 1.92 cmH₂O without masking and 6.07 ± 2.26 cmH₂O with masking. Normality was confirmed using the Kolmogorov-Smirnov test and there was no significant difference between the two means ($p = 0.702$). Figure 5 presents a complete set of data for one subject. While mean P_s remained fairly constant between sets of trials (8.50 cmH₂O without and 8.29 cmH₂O with masking), standard deviation decreased from 0.86 cmH₂O without masking to 0.29 cmH₂O with masking.

DISCUSSION

This study presents a supplement to be used with the airflow interruption system in order to obtain more consistent and accurate intrasubject data. There were no modifications made to eliminate problems associated with noise created by the airflow interruption system; rather, these problems were circumvented by adding auditory masking. Masking appeared to have aided subjects in maintaining constant glottal configuration and fundamental frequency. It

also aided in data analysis, as multiple pressure plateaus were more commonly observed during trials without masking, as those trials were subject to pronounced audio-laryngeal reflex effects. The addition of masking may have prevented these reflexes, leading to a constant intraoral volume and only one pressure plateau. It is not easy for untrained speakers to maintain constant phonation, but this is necessary for many noninvasive methods of measuring P_s .

If noninvasive subglottal pressure measurement is to be applied to the clinical setting, patients should be assisted in sustaining constant phonation. This study provides support for auditory masking as a means of doing this. Measures were taken to ensure that an improvement in consistency could be attributed to masking. The division of subjects into two groups addressed the possibility that subject comfort level could play a role in improved consistency. Trials could become more consistent as subjects become more familiar with the testing procedure. However, decreased standard deviations were observed to the same degree in group two, which performed the masking trials first. Performing a paired t-test on mean P_s addressed the issue that a decrease in standard deviation could simply be due to a decrease in the mean. The test yielded an insignificant p-value, demonstrating that this was not the case.

Replacing the airflow mask described in Jiang *et al.*, 1999 with a mouthpiece was done to isolate auditory masking as the only independent variable in the experiment. Space between a mask and the face is difficult to hold constant, as it is dependent upon both mask location and contact with the skin. By using a mouthpiece held firmly between a subject's lips and teeth, this potential source of error was eliminated. Because the mouthpiece was used in all trials, its effect did not change from the trials without masking to those with masking.

The addition of auditory masking represents an improvement over current noninvasive methods of P_s measurement. Subject-controlled labial interruption depends on an untrained subject's ability to maintain a consistent glottal configuration, which is difficult when the subject anticipates the interruption. Mechanical interruption eliminates this potential source of error, but often elicits audio-laryngeal reflexes. Auditory masking preserves the consistency of mechanical interruption while simultaneously eliminating the confounding effects of audio-laryngeal reflexes.

Subglottal pressure is an essential parameter in the aerodynamic assessment of laryngeal health. Its measurement is integral to the calculation of both vocal efficiency (20) and glottal resistance (21). When this measurement is inconsistent, variations in vocal efficiency or glottal resistance could be attributed to measurement error rather than a change in laryngeal health. However, when the measurement is accurate and consistent, it can be used as part of the diagnostic process. High levels of subglottal pressure are often characteristic of vocal pathologies (22). A simple and reliable method of measuring P_s could be used to screen patients for pathology or evaluate treatment efficacy. Easily obtainable P_s measurement is also valuable to researchers, who explore how subglottal pressure relates to other parameters of the voice and how it is affected by vocal pathologies.

In this study, the confounding effect of audio-laryngeal reflexes which often contributes to inconsistent P_s measurement was addressed by considering auditory feedback. How this addition affects other methods of measuring P_s should be investigated to determine if similar results are observed. Future studies could also focus on the effect of using auditory masking when measuring other aerodynamic parameters such as airflow or subglottal resistance.

CONCLUSION

A supplement to the airflow interruption system was described. A prerecorded sample of subject phonation was played over headphones during trials with auditory masking to prevent confounding audio-laryngeal reflexes, blocking ambient noise and providing a target pitch. Adding auditory masking increased intrasubject consistency, resulting in a more reliable method of measuring subglottal pressure. This noninvasive technique may be valuable in the clinical setting, where easily obtainable subglottal pressure measurement can be used in both the diagnostic and treatment evaluation processes.

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Figure 1. Schematic diagram of the experimentation setup. Changes from the setup employed by Jiang *et al.*, 1999 include the addition of headphones and Microsoft Voice Recorder software as well as the replacement of a mask with a mouthpiece.

Figure 2.
Mouthpiece is held inside the subject's mouth against the labial surface of the teeth.

Figure 3. Graph of subglottal pressure. (A) Firing of balloon valve, initiating airflow interruption. (A–B) Rising of intraoral pressure. (B) Equilibration of intraoral pressure with subglottal pressure. (C) End of interruption. (A–C) Total length of interruption (500 milliseconds).

Figure 4. Box plot displaying intrasubject standard deviations for normal trials (0.93 ± 0.51 cmH₂O) and auditory masking trials (0.47 ± 0.22 cmH₂O) ($p < .001$).

Figure 5. Complete data set for one subject. Mean subglottal pressure (P_s) measurement was 8.50 ± 0.86 cmH₂O for normal trials and 8.29 ± 0.27 cmH₂O for trials with auditory masking.