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Reliable Time to Estimate Subglottal Pressure

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Abstract

Measuring subglottal pressure (SGP) with complete interruption can be problematic due to unsteady plateaus in supraglottal pressure data traces during balloon valve interruption. Subjectively determining when the graph plateaus neglects the effects of laryngeal, auditory, and other physical reflexes that may alter patient effort and glottal configuration. If the SGP estimation was made at a consistent time before the onset of reflexes, the recorded pressure would not be dependent on subjective analysis by a clinician, and intrasubject data would be more precise. Previously collected data using the airflow interruption system have shown consistency at approximately 150 milliseconds (ms) after balloon valve inflation. To evaluate the validity of estimating SGP at this point, a theoretical and a physical model were applied. A theoretical ideal gas model of capacitance calculated the time necessary for supraglottal pressure to equilibrate with SGP. Using a mechanical pseudolung which served as a constant pressure source, known subresistor pressures were compared to the pressure measured by the interruption device. Both models confirmed the validity of measuring SGP consistently at 150 ms into the 500 ms interruption. In human trials testing twenty-five subjects, mean intrasubject standard deviation using this optimal time constant was 0.66 ± 0.37 cmH₂O, and 1.11 ± 0.48 cmH₂O when performing plateau analysis ($p < .0005$). This novel modification to the clinically feasible interruption model for SGP estimation demonstrates a marked improvement in the reliability of balloon valve interruption while maintaining the validity demonstrated in previous studies.

Keywords

Subglottal pressure; airflow interruption; reliable time

INTRODUCTION

Accurate estimation of subglottal pressure (P_s) easily attainable in clinical settings could allow for noninvasive detection of vocal tract pathology and provide feedback on treatment efficacy after diagnosis. Many methods have been described to measure P_s during sustained phonation, but it remains difficult to ensure accuracy while still maintaining clinical feasibility. Tracheal puncture (1) and insertion of a miniature pressure transducer into the throat through the nose (2,3) measure P_s accurately, but the procedures are invasive. Noninvasive methods measuring intraoral pressure have shown promise, but often have unreliable results and high intrasubject variability.

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A commonly used method of noninvasive P_s estimation is the technique proposed by Smitheran and Hixon (4). In this method, translaryngeal pressure and airflow are interpolated to find laryngeal resistance. Subjects repeat plosive consonants followed by voiced vowel sounds. However, this technique requires extensive subject training to ensure accuracy.

In order to avoid difficulties associated with subject-controlled interruption, methods utilizing mechanical interruption were developed. P_s estimation by controlled airflow interruption with rapidly closing balloon valves has been shown by Bard et al. to correspond well with P_s measurement through tracheal puncture in the same subject (5). While airflow interruption methods have been proven accurate, intrasubject precision remains a problem. During a trial, laryngeal reflexes are elicited by the experimental system, leading to changes in glottal configuration and P_s . This study is designed to measure P_s before the onset of laryngeal reflexes, which may lead to inaccuracies in current airflow interruption techniques utilizing a balloon valve system.

Measuring P_s at a consistent time may decrease intrasubject variability in experiments using a 500 milliseconds (ms) interruption. Intraoral pressure data traces taken in the past are characteristically similar shortly after valve closure; however, large unpredictable changes in the supraglottal pressure are difficult to avoid without extensive training. It is predicted that the supraglottal pressure measured at a reliable time of approximately 150 ms from the moment pressure starts to increase will consistently and closely estimate subglottal pressure during sustained phonation.

RATIONALE

Kearney et al. (6), using air puff stimuli to induce laryngeal reflexes, specify a minimum latency for the laryngeal adductor reflex (LAR) of 68 ms, corresponding to an R2 reflex pathway, while the shortest latency recorded experimentally was 80 ms. Average LAR latencies were between 150 and 175 ms. Vocal fold closure caused by the LAR results in an elevated level of subglottal pressure (7). During mechanical interruption, subglottal and supraglottal pressures equilibrate. Therefore, the increase in subglottal pressure noted upon reflex of the laryngeal adductors will result in an approximately equal increase in supraglottal pressure. Recording supraglottal pressure before the LAR should estimate P_s during sustained phonation more accurately than supraglottal pressure plateaus recorded after the LAR response.

In previous experiments using the airflow interruption system, we observed a consistent plateau occurring within the first 150 ms after the interruption (figure 1), before the onset of the LAR response. By estimating P_s when this plateau occurs, measurements will be more consistent while still retaining their validity. Due to the small supraglottal volume, it is possible to achieve subglottal pressure within a window of 150 ms. During mechanical interruption, the supraglottis acts as a capacitor, building charge immediately after the interruption begins. The minimum time required for equilibration can be determined using an ideal gas model of capacitance in a closed volume. To avoid velopharyngeal leaking and ensure the volume remained approximately constant, two precautions were taken. First, a nose clip was used to prevent air leakage through the nasal passage. Second, the mouthpiece was held firmly against the subject's lips to prevent leakage between the mouth and mouthpiece.

When C is capacitance, P is pressure, n is the number of moles of gas, V is the combined volume of the supraglottis and airflow interruption device (8), V_1 is the mean gas volume (derived from the ideal gas law using the atmospheric conditions of Madison, WI), R_g is the gas constant (9), and T is temperature in Kelvin:

$$\begin{aligned}
 PV &= nR_g T \\
 P &= \left(\frac{n}{V_{mol}} \right) R_g T = \frac{R_g T}{V_1}, \text{ since } V_1 = \frac{V_{mol}}{n} \\
 C(\Delta P) &= V \\
 C \left(\frac{R_g T}{V_1} \right) &= V
 \end{aligned}$$

Since $R_g = 84,784 \frac{\text{cmH}_2\text{O} * \text{ml}}{\text{mol} * \text{K}}$ (8),

And using a barometric pressure of 29 inHg (10), which equals 1001.4 cmH₂O,

$$V_1 = 25,240 \text{ ml/mol}$$

The approximate volume of the supraglottis is 38 ml (8). This volume must then be added to the volume of the interruption device, which can be calculated by multiplying the cross sectional area of the device ($\pi * (0.9525)^2 \text{ cm}^2$) by its length (12 cm). Adding the volumes of the supraglottis and the device gives the total volume of the enclosed system, 72.2 ml.

Therefore,

$$C = \frac{V * V_1}{R_g * T} = \frac{(72.2 \text{ ml}) \left(25,240 \frac{\text{ml}}{\text{mol}} \right)}{\left(84,784 \frac{\text{cmH}_2\text{O} * \text{ml}}{\text{mol} * \text{K}} \right) (298 \text{ K})}$$

After finding C, this value can be multiplied by R, the average glottal resistance (11), in order to find the time constant, τ .

$$\tau = RC = (20 \text{ cmH}_2\text{O}/\text{l/s}) * (0.00007213 \text{ l/cmH}_2\text{O}) = 0.00144 \text{ s}$$

The value for τ can then be entered into the following equation, which calculates pressure as a function of time based on a capacitance model where τ equals the time required for pressure to reach 63.2% of its final value. This model represents the filling of the supraglottal volume following balloon valve closure.

$$P(t) = P_{\max} (1 - e^{-t/\tau}) = (7.5 \text{ cmH}_2\text{O}) * (1 - e^{-t/.00144})$$

where $P_{\max}$ is equal to 7.5 cmH₂O, an average level of subglottal pressure during sustained phonation. Because pressure exponentially increases in the capacitive model as it approaches $P_{\max}$, a transglottal pressure equaling 1% of $P_{\max}$ was used as a theoretical endpoint for equilibration. This allows us to approximate the time required to fill the supraglottal volume, which can be done by entering the previously calculated value for τ and solving for t .

Doing so, we find $t = 0.00664$ seconds, which corresponds to 6.64 milliseconds. This value is within the predicted time constant of 150 ms and is significantly less than our proposed time due to the small size of the supraglottal volume. It will not take long for an average P_s of 7.5 cmH₂O during sustained phonation to equilibrate throughout an average supraglottal volume

of only 72.2 ml. Increasing or decreasing the selected level of subglottal pressure will not cause the time t to exceed 150 ms.

MATERIALS AND METHODS

Design

The experimental apparatus (figure 2) was similar to that described in Jiang et al. (12). A mouthpiece (Series 9063, Hans Rudolph, Inc., Kansas City, MO) was used instead of a mask to eliminate variability associated with mask placement, and was connected to a PVC pipe with a diameter of 1.905 cm and length of 12 cm. The mouthpiece was held in the subject's mouth between the teeth and the lips, as with a snorkel. The PVC pipe was fitted with a microphone (Radioshack) and a pressure transducer/Pneumotach amplifier (Series 1110, Hans Rudolph, Inc.). The voltage outputs of both the microphone and the pressure transducer were relayed via baby-N connector cables to a data acquisition system (model AT-MIO-16 series, National Instruments, Austin, TX), and the signals were digitized and coordinated with interruption and subject feedback (Labview custom-programmed Voice Analyzer data acquisition software program, National Instruments). An inflatable balloon valve (Series 9340, Hans Rudolph, Inc.) inflated after 1.5 seconds of phonation to interrupt subject expiratory airflow, allowing subglottal pressure and supraglottal pressure to equilibrate. The balloon requires 55 ms to inflate and the interruption lasted 500 ms. During the interruption, the entire lumen of the device is filled by the balloon, preventing any airflow escape from the device into the atmosphere, thus allowing for pressure measurement within the attached PVC pipe. A nose clip (Series 9014, Hans Rudolph, Inc.) was used to prevent airflow through the nasal cavity.

Human Subject Testing

This study was done under the approval of the University of Wisconsin – Madison Institutional Review Board. Twenty-five subjects were chosen randomly from the population in and around the University of Wisconsin – Madison with no demographic or health requirements, as the experimental system is designed to work on all types of subjects. The subjects were allowed to get accustomed to the system and the interruption; this was followed by ten trials, each lasting about five seconds, to obtain supraglottal pressure information.

A customized feedback system was employed to aid subjects in maintaining a constant glottal configuration throughout the ten trials. The Voice Analyzer program received acoustic input, and was used to monitor the amplitude and frequency of subject phonation. Continuous output was made available to the subjects. Variations in sound pressure level of $\pm 2\%$ were allowed from the desired amplitude of 72 dB, and the subjects were instructed to keep the frequency indicator at a stable, comfortable level throughout the experiment.

Data Analysis

Supraglottal pressure data traces obtained from the ten trials on each subject were analyzed with a customized LabVIEW 7.1 program. The maximum pressure achieved within the first 150 ms (figure 1) from the moment supraglottal pressure began its increase was recorded as the subglottal pressure. The same ten trials were also analyzed without a reliable time constant, and the level of subject P_s was determined to be the plateau occurring at the equilibration of subglottal with supraglottal pressure (figure 1).

A paired t-test was performed to determine if there was a statistically significant difference in intrasubject standard deviations between plateau analysis and the 150 ms reliable time constant. The test was two-tailed and a significance level of .05 was used.

In order to confirm any potential difference in standard deviation was not simply due to one method having a higher mean level of P_s , a paired t-test was performed to determine if there was a statistically significant difference in mean P_s between the two methods of analysis. This test was two-tailed and a significance level of .05 was used.

Validation of the method on a vocal tract model

To validate this technique, a mechanical pseudolung, described in Jiang et al. (12), which acted as a constant pressure source, was attached to the interruption system. This device has been used with success in the past (12, ¹³) to confirm the physical validity that our theoretical models predict. A linear pneumatic impedance device with a calibrated resistance of 20 cmH₂O/l/second (model 7100, Hans Rudolph, Kansas City, MO) was attached to model glottal resistance during phonation, resulting in airflows and subresistor pressures congruent with oral airflows and subglottal pressures in humans. The suprapressor volume was also adjusted to the average oropharyngeal volume in humans (8). Trials were run with the interruption device at subresistor pressures of 4, 7, 10, 13, and 15 cmH₂O. The pressure in the mouthpiece after 150 ms was recorded and compared to the subresistor value for each trial.

RESULTS

Human Testing

Using a reliable time constant improved the intrasubject consistency in 20 of the 25 subjects tested. Mean intrasubject standard deviation using the reliable time constant was 0.66 ± 0.37 cmH₂O, while the mean standard deviation using traditional plateau analysis was 1.11 ± 0.48 cmH₂O. A paired t-test comparing the standard deviations for each yielded a statistically significant p-value of $< .0005$ (figure 3). Mean P_s was 6.74 ± 1.87 cmH₂O using a time constant and 6.91 ± 2.05 cmH₂O using plateau analysis. There was no statistically significant difference between the two means ($p = 0.225$).

Validation on a vocal tract model

Data acquired using a mechanical pseudolung showed a strong correlation between the known subresistor pressure and the pressure measured by our airflow interruption device at 150 ms (table 1). Measurements were recorded using known pressures of up to 15 cmH₂O in order to simulate a pathological larynx which would have an elevated P_s . When compared to the subresistor pressure of the pseudolung, our device using a time constant had a slope of 1.0001 with $R^2=1$. This result corresponds to that observed in previous experiments using a mechanical pseudolung (12, ¹³). Once the mechanical balloon inflates to fill the lumen of the airflow interrupter, pressure begins to rise in the device. This experiment confirmed our hypothesis that 150 ms is a sufficient amount of time for the measured pressure to rise to that of the inputted pressure.

DISCUSSION

This study presented a new analytical technique to improve P_s measurement by rapid valve interruption. Human subject testing yielded P_s estimations that were well within the expected range as determined by invasive and noninvasive measurement techniques in previous studies (14, ¹⁵). The observed difference in intrasubject standard deviations cannot be attributed to higher average values when using plateau analysis, as there was no significant difference between the mean P_s for each method of analysis. Using a reliable time constant only decreased the intrasubject standard deviation, not the mean. It is theoretically possible that two pressure plateaus could be observed in a single data trace, thus leading to a potential difference in mean P_s measurement. If this were to occur, the second plateau could be attributed to a pressure equilibration at a different intraoral volume. In this event, the first plateau would be

representative of the true P_s and termed the intraoral pressure given the initial supraglottal capacity before any structural changes could occur.

Trials with a mechanical pseudolung validated this method, yielding accurate pressure measurements 150 ms after the closure of the balloon valve. This physical validation was strengthened by providing a theoretical ideal gas model of capacitance in an enclosed volume. To ensure this volume remained approximately constant, a nose clip was used to prevent velopharyngeal leaking. Both validation methods indicate that 150 ms is a satisfactory time at which to estimate P_s , sufficiently long to allow supraglottal and subglottal pressure to equilibrate, but short enough to avoid the effect of laryngeal reflexes.

This study represents an improvement over previous techniques of P_s estimation. Labial interruption can cause difficulties, as anticipation of the interruption can make it challenging to maintain a consistent glottal configuration, leading to inconsistent and inaccurate measurements. Complete interruption techniques have heretofore been shown to correlate well with invasive P_s measurements; however, laryngeal reflexes often interfere with this technique, resulting in unreadable and inaccurate pressure plateaus. Analyzing the supraglottal pressure data at 150 ms allows both for estimation of P_s before laryngeal reflexes occur and for quantitative data analysis, not dependent on a clinician's subjectivity.

Subglottal pressure is a key parameter of phonatory aerodynamics. It must be measured in order to calculate vocal efficiency (16) and can also be used in conjunction with airflow to find glottal resistance (13). By measuring P_s at 150 ms, we addressed both the analytical problems inherent in pressure plateau measurement and the physiological problems associated with laryngeal reflexes, offering clinicians and researchers a reliable, straightforward method of obtaining P_s data. This could be used by physicians as part of the diagnostic process. Vocal pathologies often lead to higher levels of subglottal pressure (17). A readily obtainable noninvasive measurement could be employed as a means of screening for pathology or evaluating treatment efficacy. The study also has an impact for researchers, for whom collecting data on large sample sizes is critical for developing normative databases. The new method also decreases the time necessary for data analysis, as measurements taken consistently at 150 ms are more easily recorded than those based on plateau analysis.

In this study, no changes were made to the airflow interruption device to decrease the potentially confounding effect of laryngeal reflexes. Instead, this problem was circumvented by modifying the method of data analysis. More advanced control of the subject's voice and glottal configuration with acoustic feedback systems should be investigated as a potential improvement to this technique. Future research could also focus on applying the reliable time constant to pathological subject populations, as the potential to do so was strengthened by the physical validation. Determining reliable times at which to measure other aerodynamic parameters such as subglottal resistance would also be beneficial, offering clinicians another diagnostic measurement.

CONCLUSION

A new complete interruption method was described for noninvasive subglottal pressure measurement. The supraglottal pressure achieved 150 milliseconds after the closure of a rapidly closing balloon valve was recorded as subglottal pressure, and was determined experimentally to be more precise than measurements made via analysis of intraoral pressure plateaus. Measuring P_s at a consistent time may serve as a clinical tool in the assessment of patient health and treatment efficacy, providing a simple numeric output with little inconvenience to the patient.

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Figure 1.

Intraoral pressure data trace with estimation of subglottal pressure (P_s) via a reliable time constant (A) and plateau analysis (B). The pressure recorded for (A) is that obtained by the airflow interrupter 150 ms into the 500 ms interruption. The equilibration of supraglottal with subglottal pressure yields the plateau seen at (B), which is then recorded as P_s . Pressure continues to increase after (B) due to laryngeal reflexes.

Figure 2.
Schematic diagram of the experimental setup.

Figure 3.

Intrasubject standard deviations using plateau analysis (1.11 ± 0.49 cmH₂O) and an reliable time constant of 150 ms (0.66 ± 0.37 cmH₂O) ($p < .0005$).

Table 1

Data obtained from validation trials using a mechanical pseudolung. When compared to the controlled subresistor pressure, the mean device pressure yielded a slope of 1.0001 with $R^2=1$.

Controlled Subresistor Pressure	Mean Device Pressure At 150 ms	Standard Deviation
4	4.06	0.016
7	7.04	0.005
10	10.05	0.014
13	13.05	0.005
15	15.06	0.01