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Effect of Variations to a Simulated System of Straw Phonation Therapy on Aerodynamic Parameters Using Excised Canine Larynges

Ellen R. Conroy*, Terah M. Hennick*, Shaheen N. Awan†, Matthew R. Hoffman*, Benjamin L. Smith*, and Jack J. Jiang*

*Division of Otolaryngology—Head and Neck Surgery, Department of Surgery, University of Wisconsin School of Medicine and Public Health, Madison, Wisconsin

†Department of Audiology & Speech Pathology, Bloomsburg University of Pennsylvania, Bloomsburg, Pennsylvania

Abstract

Summary: Objectives/Hypothesis—Resonance tubes are commonly used in voice therapy. These devices modify supraglottal impedance, potentially decreasing the aerodynamic power necessary for phonation. We modeled phonation with resonance tubes in excised larynges and evaluated the effects of varying tube width, tube length, and flow input on phonation threshold pressure (PTP) and phonation threshold flow (PTF). We hypothesized that the increased vocal economy observed in human subjects and several other models would be observed in excised larynges.

Study Design—Repeated measures excised canine larynx bench experiment with each larynx serving as own control.

Methods—Nine conditions were evaluated, namely control, two tube diameters (17.5 and 6.5 mm), three tube lengths (7.8, 15.0, and 30.0 cm), and three levels of flow input (80, 114, and 200 mL/s). Aerodynamic data were collected for 11 excised canine larynges attached to an artificial vocal tract, and results from each experimental configuration were compared with control.

Results—A significant decrease in average PTP occurred compared with control for the 114- and 200-mL/s flow inputs, 30-cm extension, and 17.5- and 6.5-mm constrictions. Average PTF decreased compared with control for every configuration, although statistically significant changes were only observed for 200-mL/s flow and 6.5-mm constriction.

Conclusions—Knowledge regarding the effect of vocal tract alterations could be clinically useful in determining the optimal “straw” configuration for voice therapy. Further exploration of the relationships among width, length, and flow input could provide theoretical support for the development of new therapies and resonance tube devices.

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Address correspondence and reprint requests to Jack J. Jiang, Division of Otolaryngology—Head and Neck Surgery, Department of Surgery, University of Wisconsin School of Medicine and Public Health, 1300 University Avenue, 2745 Medical Sciences Center, Madison, WI 53706. jjjiang@wisc.edu.

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Keywords

Resonance tube; Straw phonation therapy; Phonation threshold flow; Phonation threshold pressure; Excised larynx

Introduction

First proposed more than 100 years ago, phonation into resonance tubes such as plastic straws has been widely used in voice therapy and training exercises. The aim of this therapy is to facilitate production of resonant voice (ie, a voice that is neither breathy nor pressed) and maximize the sonority of the voice.¹⁻³ This is thought to be achieved via increased supraglottal pressure and acoustic impedance in the vocal tract and, consequently, lower transglottal pressure.^{1,2} Still, the exact mechanism of this technique is not well understood. Previous studies have investigated the various therapeutic aspects of straw phonation using a variety of methods. These have included human subject testing,⁴⁻⁷ theoretical modeling,^{8,9} and physical models.¹⁰ These studies found that phonation using resonance tubes, with subsequent reduction of the cross-sectional area and lengthening of the supraglottal vocal tract, decreases phonation threshold pressure (PTP). Reductions in PTP have been previously reported as an indicator of increased vocal economy and ease of phonation.^{1,9,11}

As mentioned previously, the possible decrease in PTP via straw phonation is thought to be the result of increased supraglottal pressure and vocal tract impedance.^{1,2} Impedance consists of two components, namely resistance, which removes energy from a system, and reactance, which stores energy in a system.⁹ Reactance can be further broken down into inertance, which facilitates voice initiation and self-sustained oscillation, and acoustic compliance, which inhibits self-sustained oscillation.^{2,9} Inertance (I) is defined as:

$$I = \frac{\rho L}{A} \quad (1)$$

where ρ is the density of the air column, L is its length, and A is its cross-sectional area.¹² Acoustic compliance (C) is defined as:

$$C = \frac{LA}{\rho c^2} \quad (2)$$

where ρ is the density of the air column, L is its effective length, A is cross-sectional area, and c is the speed of sound in air.² A vocal tract with high inertance is desirable for voice production for many reasons. Specifically, inertance facilitates voice initiation and self-sustained oscillation by supplying a time-delayed buildup and release of supraglottal pressure, with positive supraglottal pressure during the opening phase of the glottal cycle and negative pressure during closure (creating suction), both of which are favorable for phonation.¹² High inertance may also increase vibratory amplitude, increase source-filter interaction, and aid in achieving resonant voice owing to increased supraglottal pressure reinforcing vocal fold vibration.^{1,2,8-10}

Previous studies have looked at resonance tubes with increased length or decreased cross-sectional area as ways to modify acoustic impedance.⁹ Impedance comprises resistance and reactance, and resonance tubes are thought to increase reactance and inertance by increasing supraglottal pressure.⁹ Increased supraglottal pressure, and consequently lower transglottal pressure, causes the vocal folds to become slightly abducted. This creates a more ideal

matching of glottal impedance to input impedance, as well as increased source-filter interaction, with both of these factors resulting in potential improvements in vocal economy.^{8,13} In addition, lower transglottal pressure results in more cushioning for vocal fold collisions owing to increased pressure at the glottis.¹

Supraglottal pressure has traditionally been increased using constrictions of the vocal tract, and the interdependence of supraglottal pressure and impedance makes it unreasonable to fully separate the two. Several studies^{1,9,11} have found that straw phonation therapy increases acoustic impedance and supraglottal pressure, thereby improving vocal economy and reducing PTP. However, no studies to date have evaluated the addition of an oppositional flow as a method of increasing supraglottal pressure and vocal economy. Supplying constant positive pressure to the vocal tract may increase supraglottal pressure and impedance, facilitating the slightly abducted glottal configuration, which is ideal for low impact vocal fold oscillation. As an alternative method of influencing supraglottal pressure and impedance versus straw phonation, the use of oppositional flow may allow for increased control over supraglottal pressures without the necessity for multiple straw lengths and diameters. In this study, we altered supraglottal pressure and impedance in an excised larynx bench apparatus using tube extensions, tube constrictions, and oppositional airflow in order to determine their effect on phonatory aerodynamics. We hypothesized that the increased vocal economy observed in human subjects and several other models could be produced in excised larynges, and that decreasing tube width, increasing tube length, and increasing simultaneous flow input would result in a decrease in PTP and phonation threshold flow (PTF) relative to control trials.

Materials and Methods

Data collection

Larynges—A total of 11 larynges of approximately the same size were acquired postmortem from mongrel dogs that were sacrificed for purposes unrelated to this study. Excision of the larynges followed the method described by Jiang and Titze.¹⁴ On excision and verification of the absence of pathologies or trauma, larynges were stored in 0.9% saline solution in a freezer until the experiment.

Apparatus—The excised larynx bench apparatus (Figure 1) used is designed to simulate the human respiratory system. Pressurized subglottal airflow is passed through two humidifiers (Concha Therm III, Fisher and Paykel Healthcare, Inc., Laguna Hills, CA) in series to humidify and warm the air. Airflow is measured using an airflow meter (model FMA-1601 A; Omega Engineering, Inc., Stamford, CT) and manually controlled during the experiment using a needle valve. Pressure is measured directly below the larynx using a digital pressure meter (901 series; Ashcroft, Inc., Stratford, CT). Airflow and pressure are recorded simultaneously at a sampling rate of 100 Hz using a data acquisition board (model ATMIO-16; National Instruments, Corp., Austin, TX) and customized *Lab-VIEW* 8.2.1 software (National Instruments, Corp., Austin, TX). The apparatus is housed in a triple-walled, sound-attenuated room to reduce background noise and stabilize humidity levels and temperatures.

Excised larynx procedure—The larynx was mounted on the bench apparatus as specified by Jiang and Titze.¹⁴ A metal hose clamp was used to secure the trachea to a pipe that was connected to the pseudolung. The arytenoid cartilages were stabilized bilaterally using three-pronged micrometer devices, allowing for precise control of vocal fold position. The laryngeal prominence was sutured to a third micrometer, allowing for precise control of

vocal fold elongation. Vocal fold elongation and adduction were constant across all trials conducted with a single larynx.

Experimental conditions—Five trials were completed for each of following conditions (modeled in Figure 2):

1. **Control:** For control trials, only an artificial vocal tract is used. This artificial vocal tract consists of two parts: the first is a larynx insert that allows the tract to be placed securely within the epilarynx; the second part contains a one-way valve and port to provide the airflow input. This port was occluded during trials not using a simultaneous airflow input. The larynx insert has a small tube, which is placed at the level of the false vocal folds and a conical transition to a larger tube, which is connected to the airflow input piece. The small tube has an inner diameter of 6 mm and length of 25 mm. The conical transition section is 25 mm in length and the larger tube has an inner diameter of 25 mm and a length of 25 mm. This part of the vocal tract was made using acrylonitrile butadiene styrene plastic. The second piece including the airflow input port was made of polyvinylchloride pipe. In the control condition, no additional extension, constriction, or flow input to the vocal tract was provided.
2. **Airflow input:** For trials with airflow, supraglottal airflow input was provided via an external flow source. Three levels of airflow input were assessed (80, 114, and 200 mL/s). No additional extension or constriction to the vocal tract was provided.
3. **Constrictions:** For trials with a constriction, the airflow port was occluded and a constriction was placed at the uppermost aspect of the vocal tract (exit of the piece containing the airflow input port). Two levels of constriction (tube diameters of 17.5 and 6.5 mm) were assessed. No additional extension or airflow input to the vocal tract was provided.
4. **Extensions:** In this condition, the airflow port was occluded and an extension was attached to simulate the use of a straw. Three levels of tube length (7.8, 15.0, and 30.0 cm) were assessed. The inner diameter of each tube was 17.0 mm. No additional airflow input to the vocal tract was provided.

Each vocal tract addition was sealed to the epiglottis using tissue glue (Loctite 401 Instant Adhesive, Part No. 40104; Henkel Corporation, Düsseldorf, Germany). Condition order was randomized to eliminate any potential confounding effect of task order, such as dehydration or fatigue. Nine possible configurations (control, three levels of airflow input, two levels of constriction, and three levels of extension) were tested in succession in a randomized order. To initiate phonation, subglottal airflow was manually increased slowly and consistently until phonation began. Airflow was then kept constant for approximately 5 seconds of phonation, at which point subglottal airflow was stopped. Trials were separated by approximately 3-second periods of rest. The vocal folds were kept hydrated by frequent application of 0.9% saline solution between trials.

Data analysis

For the purposes of this study, data analysis focused on measures of PTP and PTF. Mean PTP and PTF were calculated for each larynx for each condition. Average PTF and PTP were determined manually for each trial using traces of pressure or flow over time. Values of pressure and flow over the 5-second interval of each trial were averaged to obtain the mean PTP or PTF for the trial; average values over the duration of the trial were approximately the same as the specific value obtained at the precise phonation onset. Mean values for each of the eight experimental configurations were compared with control trials using a repeated measures analysis of variance (ANOVA) with Dunnett's pairwise

comparisons. If data did not meet assumptions for parametric testing, a Friedman repeated measures ANOVA on ranks was performed. *SigmaPlot* 11.0 (Systat Software, Inc., Chicago, IL) was used for all analyses. Effect sizes between group means (Cohen's *d*) were computed using an online analysis program¹⁵ based on the method described by Cohen.¹⁶ Corrections were made for intralarynx comparisons according to the method described by Morris and DeShon.¹⁷

Results

Overall, there was a significant difference in the PTF means among the experimental conditions ($P = 0.006$). Specifically, significant decreases in PTF relative to control trials were observed for 200-mL/s flow input and 6.5-mm constriction (Figure 3). In addition, there was a significant difference in the PTP means among the experimental conditions ($P < 0.001$). Specifically, significant decreases in PTP relative to control trials were observed for 114- and 200-mL/s flow, 30-cm extension, and 17.5- and 6.5-mm constriction (Figure 4). Only the 80-mL/s flow and 7.8- and 15.0-cm extensions did not result in a significantly lower PTP. Summary data for PTF and PTP are displayed in Table 1. Relatively high standard deviations are owing to four larynges, which had a high PTP across conditions, although they still exhibited decreased PTP with each modification relative to control trials.

Discussion

This study modeled the effects of changing impedance and supraglottal pressure on phonatory aerodynamics in an excised larynx bench apparatus through the addition of extensions, constrictions, and simultaneous airflow via a synthetic vocal tract. We expected each vocal tract addition to correlate with decreased average PTP and PTF. This hypothesis was largely supported by our results for PTP, but only slightly supported by our PTF results.

Significant decreases in PTP were observed for all conditions except the flow input of 80 mL/s, and the 7.8- and 15.0-cm extensions. These results reinforce the concept that vocal tract extensions and constrictions improve vocal economy and increase the ease of phonation.^{1,9,11} In addition, significant decreases in PTP observed for two of the direct airflow inputs (114 and 200 mL/s) indicate that improved presumed vocal economy can be achieved by varying parameters other than the obvious vocal tract extensions or constrictions offered via the specific use of a tube or straw. The modifications to the vocal tract apparently increased inertance, facilitating voice initiation and self-sustained oscillation, thereby improving vocal economy. It is interesting to note that there was a statistically significant decrease for both constrictions, as decreasing cross-sectional area increases inertance, while at the same time decreasing compliance. This may be particularly advantageous for voice production. The lack of a statistically significant decrease in average PTP when 80-mL/s flow was administered and the two shorter extensions were added may be owing to these vocal tract alterations being insufficient to meaningfully affect supraglottal pressure and impedance, and specifically, inertance. This may have been because the magnitude of these modifications was small when compared with the length of the artificial vocal tract. As the artificial vocal tract is an extension of the supraglottis, the average size of the supraglottis used may have affected the relative percent increase in overall vocal tract length as well. For example, adding a known length extension to a smaller vocal tract would necessarily result in a greater percent increase in length than the same extension added to a greater length vocal tract. The result would be a greater decrease in PTP for the shorter vocal tract than for the longer tract. The same reasoning may explain why low flow inputs were not observed to meaningfully increase supraglottal pressure and impedance. A relatively small oppositional flow into a smaller vocal tract volume would lead to a greater percent increase in pressure and possibly greater decreases in PTP versus

relatively little change in pressure and PTP if the same flow were to be applied to a larger vocal tract. Therefore, small but meaningful variations in factors such as extension length or oppositional flow may be required to result in increases in supraglottal pressure and inertance, and decreases in PTP. Regardless, the results of this study show consistent trends for changes in PTP observed across all larynges, including four larynges, which had high PTP in the control condition (17.02, 14.45, 20.38, and 21.30 cm H₂O). Measures from these four larynges led to the relatively high standard deviations reported in Table 1, whereas the PTP measures obtained for the other seven larynges in the control condition were relatively low (range: 1.97–9.53 cm H₂O).

Decreases in PTF were observed across conditions; however, these changes were only significant with the addition of a 6.5mm constriction or with a flow input of 200 mL/s. The PTF is a relatively recently proposed parameter¹⁸ affected by vocal fold length, vocal fold thickness, mucosal wave velocity, and prephonatory glottal half-width. Because vocal fold characteristics did not change across conditions, and glottal configuration was also held constant, changes in mucosal wave velocity (a parameter present in the equations for both PTF¹⁸ and PTP¹⁹) may be responsible for the decreases that were observed. Decreased transglottal pressure owing to an increase in supraglottal pressure should decrease mucosal wave velocity, thus decreasing the aerodynamic energy required to reach the phonation threshold. Importantly, changes in PTP are proportional to changes in mucosal wave velocity, whereas changes in PTF are related to the square root of these changes. Therefore, more extreme modifications to the resonance tube configuration (eg, a 50-cm extension) may be required to yield greater changes in PTF. It is notable that PTF was significantly lower in the conditions in which the smallest constriction was used and the condition where the largest flow input was added. This increase in flow, or increase in the amount of air being supplied to the system, was sufficient to modify supraglottal pressure and inertance, leading to the statistically significant decrease in PTF.

It should be noted that, although the subglottal airflow input was humidified, the supraglottal airflow input used in this study was not humidified. As PTP and PTF are sensitive to dehydration,^{20,21} future experiments may observe even more drastic decreases in threshold aerodynamics if humidified air were used. In addition, aerodynamic parameters were used as a surrogate for vocal economy, but it is important to note that vocal economy was not directly measured. However, because the precise measurement of variables such as vocal fold impact intensity and vocal economy that are difficult to measure *in vivo* may be measured under controlled conditions *ex vivo*, it is our expectation that future studies using excised larynges may provide insight regarding these parameters.

This preliminary study demonstrated how the effects of vocal tract extensions or constrictions as used in straw therapy might be simulated using the excised larynx bench apparatus. In addition, this study also evaluated whether a novel modification, oppositional airflow, might also be used to achieve the same effects observed with traditional vocal tract extensions or constrictions. Significant changes in PTP and PTF were observed for various tube configurations and oppositional flow conditions, and it is our view that the PTP and PTF changes observed in this study are likely attributable to direct effects on supraglottal pressure and impedance. In particular, increased inertance and improved matching of glottal impedance to input impedance may have been factors in achieving the observed PTP and PTF changes observed in this study. It remains to be demonstrated whether specific length-diameter combinations of tubes can optimize the process of impedance matching. To address this issue, future studies will be conducted to investigate which factor (extension, constriction, or flow) has the most beneficial effect on phonation and which combination is optimal. Furthermore, supraglottal pressure will be measured for all larynges in upcoming studies to reveal insight into which pressure level is optimal. In addition, the finding that

administering a direct airflow to the vocal tract decreases PTP and thus apparently increases vocal economy and ease of phonation may be used to alter or supplement current methods of straw phonation therapy. Voice therapy that includes direct airflow input may be achieved via a constant flow source (such as the widely available continuous positive airway pressure devices for home use) or other device at the mouth that allows for varying levels of airflow input and can be used alone or with extensions and constrictions. The use of oppositional airflow to achieve decreased PTP and increased vocal economy without the necessity of a straw or tube extension may allow for the development of voice therapy tasks that can include natural speech elicitations rather than the restrictive vowel-like or simple consonant-vowel syllable productions (eg,/vu/⁴) used in current straw phonation therapies.

It is our expectation that prospective studies will further explore the mechanism(s) by which reductions in PTP occur and ultimately apply these methods to human subjects. The range and combination of modifications determined to be optimal in canine larynges may serve as a starting point for investigating the range and combination that is most beneficial for voice therapy in humans. Our simulated system of straw phonation therapy may be used in conjunction with human larynges to more precisely determine the optimal range and configuration. This refined range could then be applied and tested using human subjects. Aerodynamic as well as acoustic and electroglottographic testing of human subjects both during and immediately after vocal exercises with tube extensions, constrictions, and direct flow inputs (or combinations of these vocal tract additions) will provide additional information on the short- and long-term effects of these vocal tract alterations in humans. These investigations could eventually lead to the development of more efficient methods of voice therapy, thus potentially decreasing therapy duration or the need for invasive intervention.

Conclusions

The beneficial effects of straw phonation therapy seen in previous studies were investigated in a new model using an excised bench apparatus. Extensions and constrictions of the simulated vocal tract and the addition of a direct flow input into the supraglottal vocal tract largely resulted in significant decreases in PTP. Changes in PTF were more variable, possibly because the vocal tract modifications were not extreme enough or insufficient data were collected. These results verify the use of an excised bench apparatus in simulating methods such as straw phonation therapy and suggest that decreases in PTP and PTF, and overall improved vocal economy may be achieved not only using vocal tract extensions and constrictions but also via direct flow input into the supraglottal vocal tract.

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Figure 1.
Schematic of experimental setup. CPAP, continuous positive airway pressure.

Figure 2.

Schematic of vocal tract configurations. For control trials, only the base vocal tract is used. For trials with airflow, the extension is removed, there is no constriction, and airflow input is provided via an external flow source. For trials with an extension, the airflow port is occluded and an extension is attached. For trials with a constriction, the airflow port is occluded, the extension is removed, and a constriction is placed at the location specified.

Figure 3. Average change in phonation threshold flow relative to control for each condition. Left, oppositional airflow; middle, extension; right, constriction. The error bars represent standard error.

Figure 4. Average change in phonation threshold pressure relative to control for each condition. Left, oppositional airflow; middle, extension; right, constriction. The error bars represent standard error.

Table 1
Summary Data for Each Condition

Condition	PTF	Cohen's <i>d</i>	PTP	Cohen's <i>d</i>
Control	14.1 ±4.1	—	9.16±7.4	—
200-mL/s flow	12.0 ± 2.9	0.590	7.58±6.1	0.224
114-mL/s flow	13.1 ±4.2	0.240	8.04±6.6	0.160
80-mL/s flow	12.9±3.3	0.321	8.09 ±6.8	0.151
7.8-cm extension	13.4±4.0	0.158	8.18±6.7	0.139
15-cm extension	14.0 ±3.7	0.009	8.29±6.5	0.126
30-cm extension	12.8±4.3	0.317	7.40±6.1	0.265
6.5-mm constriction	12.3±3.8	0.461	7.71 ±6.3	0.213
17.5-mm constriction	12.6±3.5	0.388	7.92 ±6.5	0.178

Abbreviations: PTF, phonation threshold flow; PTP, phonation threshold pressure.

Notes: Values are presented as mean ± standard deviation. Cohen's *d* values represent effect sizes for intralarynx comparisons.