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Aerodynamic and Acoustic Effects of Ventricular Gap

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Abstract

Purpose—Supraglottic compression is frequently observed in individuals with dysphonia. It is commonly interpreted as an indication of excessive circumlaryngeal muscular tension and ventricular medialization. The purpose of this study was to describe the aerodynamic and acoustic impact of varying ventricular medialization in a canine model.

Methods—Subglottal air pressure, glottal airflow, electroglottograph, acoustic signals and high-speed video images were recorded in seven excised canine larynges mounted in vitro for laryngeal vibratory experimentation. The degree of gap between the ventricular folds was adjusted and measured using sutures and weights. Data was recorded during phonation when the ventricular gap was narrow, neutral, and large. Glottal resistance was estimated by measures of subglottal pressure and glottal flow.

Results—Glottal resistance increased systematically as ventricular gap became smaller. Wide ventricular gaps were associated with increases in fundamental frequency and decreases in glottal resistance. Sound pressure level did not appear to be impacted by the adjustments in ventricular gap used in this research.

Conclusions—Increases in supraglottic compression and associated reduced ventricular width may be observed in a variety of disorders that affect voice quality. Ventricular compression may interact with true vocal fold posture and vibration resulting in predictable changes in aerodynamic, physiologic, acoustic, and perceptual measures of phonation. The data from this report supports the theory that narrow ventricular gaps may be associated with disordered phonation. In vitro and in vivo human data are needed to further test this association.

Keywords

Excised canine larynx; ventricular fold; glottal flow resistance; medial compression; ventricular gap

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INTRODUCTION

The ventricular folds make a laryngeal constriction above the true vocal folds. They are separated from the true vocal folds by the laryngeal ventricle and usually are positioned lateral to the true vocal folds resulting in a large gap between the ventricular folds. This gap decreases during medial compression needed for some articulatory speech gestures. Medial compressions of the laryngeal ventricles are routinely credited with playing an important role during vegetative functions such as swallowing and valsalva maneuvers.^{1,2} Too little is known about the impact of supraglottic laryngeal anatomy and physiology for speaking and singing.³⁻⁵ While it is generally assumed the supraglottic structures contribute little to phonation, some reports suggest otherwise. Finnegan and Alipour⁶ found that ventricular compression and removal of the ventricular folds appeared to impact true vocal fold vibration in the excised canine larynx.

During phonation, the average distance between the two ventricular fold is maintained by the laryngeal and ventricular muscles to prevent unwanted ventricular fold vibration. This gap is usually larger in males (mean = 6.1 mm) than in females (mean = 4.4 mm).⁷ The major muscle components of the ventricular folds are the lateral thyroarytenoid (TA) and the ventriclurais muscle, where the TA bundles are much larger and located in the lateral part of the true and ventricular vocal folds.⁸ According to Reidenbach,⁹ ventricularis and lateral TA muscles that she called anterolateral, anteromedial and posteromedial muscles, contribute to the abduction and adduction of ventricular folds. When the function of some of these muscles is disrupted or when the ventricular folds become larger than usual, the ventricular gap decreases. A decreased ventricular gap was shown to have major aerodynamic and acoustic effects during the phonation of excised canine larynges.^{6, 10}

Kucinski *et al.*¹¹ studied the airflow through a scaled-up static Plexiglas model of the larynx. They included two sets of modeled ventricular folds that differed in the space or gap between the folds. They found that airflow in the glottis was laminar for all flow rates and all geometries they studied. They reported that a narrow gap accelerated and straightened the glottal jet. On the other hand, a wide gap behaved similar to the model without ventricular folds.

When the ventricular gap decreases, aerodynamic pressure in the laryngeal ventricle increases.¹² In an excised canine larynx study, Alipour and Scherer¹² measured the ventricular air pressure during phonation using a transducer attached to a hypodermic needle inserted in the laryngeal ventricle. They reported that the larynges with larger ventricular gaps had lower ventricular pressure than those with narrower ventricular gaps. The ventricular gap in the canine larynx is generally smaller than in the human larynx and may simulate the extreme conditions that could arise in the pathologic human larynx.

In humans, supraglottic activity may result in a reduction of ventricular area and may be interpreted as a physiologic correlate of dysphonia. However, some reports have suggested the issue is more complex. Stager *et al.*^{13, 14} examined supraglottic compression in normal control and voice disordered speakers. They reported evidence of significantly greater “static” (consistent across voicing tasks) supraglottic compression in disordered speakers. The authors defined “dynamic” compression as that which occurred inconsistently and was associated with specific speech activities. They suggested dynamic compression may be a characteristic of normal speech during which the larynx plays an articulatory function, such as during production of glottal stops.

Behrman *et al.*⁴ similarly reported findings of supraglottic compression in individuals with normal voice and individuals experiencing dysphonia. They did not differentiate between

static and dynamic compression. Based on their observation that the width dimension was commonly present in normal speakers, they concluded that the anterior-posterior dimension of supraglottic compression was more indicative of dysphonia than was the width dimension.

Supraglottic compression or decreases of supraglottic gap has been observed in individuals with a variety of voice and laryngeal pathologies. Stager et al.¹³ reported that 68% of patients with vocal nodules and 80% of patients with muscle tension dysphonia demonstrated visible evidence of supraglottic compression. Steffen et al.³ described differences in ventricular vocal fold shape in patients with unilateral vocal fold paralysis during phonation compared to respiration. Bielamowicz et al.¹⁵ observed more ventricular fold activity in unilateral vocal fold paralysis patients who had normal vocal function measures than in similar patients with abnormal measures suggesting evidence of effective compensation in those who performed better.

In an excised canine larynx study, Alipour and Finnegan¹⁶ investigated the acoustic effects of supraglottic structures and found that a canine larynx with active supraglottic structures produced louder sound, had higher phonation threshold pressure (PTP) and had a limited range of frequency changes. This was likely due to the decreased glottal gap and higher glottal flow resistance common in canine larynges which have normally more active ventricular folds due to its smaller ventricular gap than human larynges. Despite this difference the pathologic human larynx shares similarities with and may be modeled by the excised canine larynx. The phonatory characteristics of excised canine larynx are very similar to those of excised human larynx.¹⁷

This study is an extension of Alipour and Finnegan¹⁶ study. The purpose is to quantify the effects of ventricular gap on the glottal flow resistance, fundamental frequency, and sound pressure level.

METHODS

Nine excised canine larynges were obtained following cardiovascular research experiments at the University of Iowa Hospitals and Clinics. The larynges were removed from the animal after death, quick frozen in liquid nitrogen and stored in a -82 °F freezer. The frozen larynges were later transferred to our lab freezer and stored until the day of experiment. They were thawed in saline solution overnight in the refrigerator before the preparation for the experiments. The gender and weight of the larynges are provided in Table 1. Excised larynges were mounted and operated according to previous work.¹⁰

Adduction of the true vocal folds was controlled by a pair of sutures pulling on the muscular process of each arytenoid cartilage to simulate lateral cricoarytenoid and (lateral) thyroarytenoid (TA) muscle action, as in an arytenoid adduction (Figure 1). The true vocal folds adduction levels were adjusted using weights (50–150 grams) that pulled the sutures attached to the muscular process of the arytenoid cartilages. Due to the special canine laryngeal anatomy, the movement of arytenoid for true vocal folds adduction can cause some ventricular fold adduction too. However, the ventricular (Lateral) gap was controlled separately with bilateral sutures attached to the epiglottis. By making medial anterior incisions in the epiglottis (see Figure 1), a larger gap setting was possible. In some of the larynges, a sustained oscillation was established and then ventricular gap was varied periodically by pulling the sutures (stretching and releasing) every 2 seconds.

The subglottal pressure signal was recorded using a pressure transducer (Microswitch 136PC01G1) mounted perpendicular to the flow in the tracheal tube 10 cm below the vocal folds with the end of the transducer near the tracheal wall. The flow rate signal was recorded

with a pneumatic flow meter (Rudolph 4700) and low-range pressure transducer (Validyne DP103) upstream of the humidifier (ConchaTherm[®] unit, RCI Laboratories). The mean values of subglottal pressure and flow rate are used for the calculation of glottal resistance. The ratio of pressure to flow rate is simple resistance and the overall slope of pressure-flow curve is the differential glottal flow resistance.

The electroglottograph (EGG) signal was obtained by placing electrode plates from a Synchronvoice electroglottograph on the thyroid lamina (anterior side of larynx) during phonation. The electrodes were positioned while the larynx was oscillating and the EGG signal was monitored on the oscilloscope to assure a good signal. The electrodes were secured in place with a narrow strip of duct tape. The amount and the movement of the tissues between EGG electrodes determine the shape and amplitude of the EGG signal.

The audio signal was obtained with a microphone (Sony ECM-MS907) at a distance of 15–20 cm from the larynx and recorded on a digital audio tape recorder (Sony PCM-M1). The sound pressure level (SPL) was measured with a type 2 sound level meter (Extec model 407738) with “C” weighting and “fast” averaging, placed about 15 cm from the larynx.

For each excised larynx, the manipulated variables were the ventricular gap adjusted with sutures and two levels of adduction (low and high corresponding to 50, 150 grams weights applied to both adduction sutures). Once the degree of ventricular gap and adduction was established, two pressure-flow sweeps were performed, in which flow was gradually increased or decreased with a rotary control valve (consequently altering pressure as well) to determine the range of aerodynamic conditions during which the vocal folds would vibrate (Table 1). Recordings of oscillation of the vocal folds in slow motion were visualized with a strobe light.

High-speed imaging was performed with a monochrome camera (Photron, model 100K Fastcam- 1024-PCI). The larynx was illuminated with a Lowel Pro light at a distance of about 50 cm. For each ventricular gap, a brief recording of the superior larynx was recorded, first with a piece of printed grids on the ventricle and then without the grids. These images were used to measure the ventricular area and gap before each experiment. First an image of a millimeter grid laid on the fold is acquired then an image without the grid. The area was measured and calibrated using image processing toolbox of MATLAB, by tracing the edge with cursor. Also, the recorded video frames were later converted to kymographic images in MATLAB using custom-made software.

Analog signals from the EGG, microphone, and pressure and flow transducers were recorded simultaneously onto a Sony SIR1000 digital tape recorder at a sampling rate of 40 kHz per channel. These recorded signals were later digitized using a 14-bit A/D converter (DATAQ Instruments). The signals were then converted to calibrated physical quantities in a MATLAB routine and used for the aerodynamic and acoustic analyses.

Statistical analysis was performed using Microsoft Excel 2010 to determine if there were significant differences between glottal resistances across different gap conditions. Unpaired t-tests with the significance level of $p=0.05$ was used.

RESULTS

Table 1 shows the aerodynamic and acoustic measurement ranges of the excised larynges in this study. The ranges of subglottic pressure were controlled and, therefore, were very similar. The ranges of flow rate demonstrated variations that may have been due to the size, adduction, and function of the larynges. The sound pressure level ranged from 60–82 dB and frequency ranged from 70–200 Hz.

Figure 2 shows glottal waveforms and kymographic images of the excised larynx #1 with a neutral ventricular gap position. The top graph is the kymographic image calculated at 40% of the vocal fold length from the posterior glottis. Below the kymographic image are the electroglottograph (EGG), subglottal pressure (Ps), and flow rate (Flow) waveforms. The larynx oscillated regularly with a mean subglottal pressure of 14.1 cm H₂O, a mean flow rate of 1.05 l/s, sound pressure level of 71.2 dB and at a frequency of 69.9 Hz. The EGG signal was used for pitch detection and calculation of closed quotient value of 0.328. The subglottal pressure and flow signals have two peaks that indicate a resonance in the larynx or below it. Examination of the video recordings of the larynx indicated that in addition to true vocal fold oscillation, the ventricular folds also oscillated with a similar frequency. The kymographic image shows the peaks of true vocal folds (darker teeth) are not aligned with the peaks of false vocal folds, suggesting a phase difference between true and false fold closure. The duration of the kymograph is about 66.6 ms and is not synchronized with glottal waveforms.

Figure 3 shows glottal waveforms and a kymographic image of the same larynx with a wider ventricular gap position. The waveforms are the same as in Figure 2. The larynx oscillated regularly with a mean subglottal pressure of 12.1 cm H₂O, a mean flow rate of 1.03 l/s, sound pressure level of 70.7 dB and at a frequency of 82.8 Hz. The EGG signal shows a drastic change with narrower pulse, suggesting a shorter closure time. The closed quotient is about 0.24.

To compare vocal fold dynamics of these two oscillations, we can compare the FFT spectra of their EGG and microphone signals. Figure 4 shows FFT signals corresponding to waveforms in Figure 2. The top spectrum of the EEG signal reveals the pattern of vocal fold motion and their contacts. Most of the energy is concentrated in the first four partials with average slope of -15.9 dB/octave. The bottom graph shows the spectrum of the microphone signal with an average slope of -6.4 dB/octave and a strong second partial (H1-H2=3.6 dB).

Figure 5 shows the FFT spectra of EGG and microphone signals for waveforms of Figure 3. The EGG spectrum shows a drop in slope (-6.2 dB/octave) and strong higher partials, suggesting a more complex vibration pattern. This might be due to the fact that the more opened ventricular gap allows the true vocal folds oscillate better. The spectrum of the microphone signal shows an increase in slope (-8.9 dB/octave) and diminished higher partials compared to the corresponding graph in Figure 2.

During phonation of the excised canine larynx the ventricular folds oscillate frequently as observed and reported previously by Alipour and Finnegan.¹⁶ This ventricular oscillation creates time varying ventricular area and ventricular gap. Using high-speed imaging of the superior view, the ventricular gap was established and measured in this study as described in the “Methods”. Figure 6 shows ventricular gap data derived from the high-speed imaging of an excised canine larynx oscillating with mean subglottal pressure of 20 cm H₂O, mean flow rate of 390 ml/s, sound pressure level of 73.6 dB, and oscillating at a fundamental frequency of 122.8 Hz. The ventricular gap (Figure 6, bottom) changes from 0.7 mm to 2.5 mm during oscillation. These values are much smaller compared to human ventricular gap values.⁷ However, with medial-anterior incision in the epiglottis, large FVF oscillations with amplitude as large as 3 mm (gap sizes of 0 to 6 mm) were observed in some canine larynges.

The ventricular width (gap) was changed dynamically by manipulating the bilateral sutures. While the larynx was oscillating at a mean subglottal pressure of 20 cm H₂O, the ventricular width was manually changed by stretching and releasing the sutures. Figure 7 shows a portion of glottal waveforms before and after ventricular width widening. There are 3 signals including EGG, subglottal pressure, and flow rate from top to bottom. The solid lines

are waveforms for the larynx with a narrow ventricular gap and the dashed lines are for the widened gap. In the narrow gap condition the ventricular fold oscillation produced the double peak EGG signal. The additional peak is due to the ventricular fold contact. Also, the subglottal pressure was much higher and the flow was lower in narrow gap condition. In the wider gap condition, the ventricular gap almost doubled compared to the narrow gap condition, and second EGG peak disappeared.

The pre-phonatory value of the ventricular gap (its static value) was established before the experiment and was measured from high-speed imaging. Figure 8 allows comparison of pressure flow relationships from larynx #4 during three ventricular gap conditions. The data suggests the narrower gap generated higher subglottal pressure than neutral and wider gaps.

The mean and standard deviation values of sound pressure level (SPL), fundamental frequency (F0), and glottal flow resistance (GR) for three groups of neutral gap, wide gap, and narrow gap are shown in Figure 9. The mean SPL appears to be similar in all groups with no significant differences. However GR and F0 are significantly different between wide and narrow gap conditions ($p=0.025$ for GR and $p=6 \times 10^{-5}$ for F0). The narrow condition resulted in the highest glottal resistance and wider condition resulted in the lowest glottal resistance. The fundamental frequency was highest in wider condition.

DISCUSSION

This study examined the aerodynamic and acoustic effects of the ventricular gap in excised canine larynx. The gap ranged between 1–2.5 mm in the canine which is much smaller than the human ventricular gap (about 6 mm). This narrow gap appears to have caused the oscillation of the ventricular folds in the canine that does not normally occur in human larynges. However, it demonstrates similarities with what may occur in human larynges when the ventricular gap is narrowed due to some pathological conditions.

The small ventricular gap in the canine larynges results in increased ventricular pressure.¹² Similar findings are likely in humans who have small ventricular gaps due to tissue changes such as enlarged ventricular folds resulting from edema secondary to laryngitis or polypoid degeneration (Reinke's edema) or due to hyperfunction resulting from excessive circumlaryngeal muscular effort as in muscle tension dysphonia. When the ventricular folds are abnormally close to each other as a result of abnormal tissue changes or excessive muscular effort, aerodynamic pressure and resistance can be expected to increase. Such increases should result in predictable, albeit variable changes in acoustic output. In the case of edema without increased muscular tension, fundamental frequency may be expected to be low. When laryngeal tissue is normal but laryngeal muscle tension is increased fundamental frequency may increase. The impact on voice quality may also be variable.

Behrman et al.⁴ reviewed videostroboscopic images of 40 dysphonic patients and 40 normal controls. They reported that anterior-posterior ventricular compression was significantly greater in the dysphonic group. They clarified, however, that since ventricular compression appeared to be present in some of the normal controls, additional variables were likely involved. A similar interpretation was offered by Stager et al.¹⁴ based on a much smaller pool of subjects. Woo et al.¹⁸ noted that excessive ventricular compression and anterior-to-posterior laryngeal compression were prevalent among 62 patients with persistent or recurrent dysphonia after laryngeal surgery. Other physiologic abnormalities were also described. Kelchner et al.¹⁹ described supraglottic phonation in 21 children who underwent airway reconstruction surgery. Multiple sources of supraglottic vibration were observed but the impact on perceived severity scores of dysphonia was variable and ranged from

moderate to severe. Bielamowicz et al.¹⁵ reported ventricular compression among patients with unilateral vocal fold paralysis.

Ventricular activity during speech has received relatively little attention in the voice literature. Some reports describe ventricular vocal activity as abnormal and associated with dysphonia in some individuals. For example, some manifestations of muscle tension dysphonia have been associated with ventricular compression.^{4,13,14,20,21} The current study used a canine model to approximate the likely supraglottic configurations that may be associated with increased supraglottic muscular effort seen in humans and referred to as muscle tension dysphonia.

The data are consistent with previous studies demonstrating that as ventricular gap becomes smaller subglottal pressure and glottal resistance both increase in predictable fashion. Mean subglottal pressure and mean glottal resistance were lowest when glottal gaps were wide and highest when gaps were narrow. Glottal resistance measured when ventricular gap was neutral fell between measures for wide and narrow gaps.

The magnitude of some differences across conditions appeared to be influenced by magnitude of transglottal airflow. For example, a subglottal pressure of 10 cm H₂O was measured during the neutral gap condition when transglottal flow rate approximated 400 ml/s. This same subglottal pressure of 10 cm H₂O was measured during the narrow gap condition when transglottal flow was only 200 ml/s. Interestingly, however, the magnitude of this difference diminished as transglottal airflow rate increased. At transglottal airflow rate of approximately 1100 ml/s, subglottal pressure during the neutral and narrow ventricular gap conditions were very similar at 24 cm H₂O. Taken together these findings suggest that increases in subglottal pressure occur more readily with respect to increases in transglottal flow rate in the narrow gap condition. The impact on fundamental frequency was unexpected, however. Both wide and narrow gaps yielded fundamental frequency measurements that were higher than measures obtained with neutral gaps.

These data may be interpreted as evidence that a circular negative impact on phonation may occur due to reduced ventricular gap width. As gap width becomes smaller and transglottal resistance increases, the speaker may respond with increased phonatory effort. This effort may result in additional narrowing of ventricular width, further increasing transglottal resistance and compounding the problem.

CONCLUSIONS

This report is an investigation of the effects of ventricular gap (false folds gap) on the aerodynamics and acoustics of the excised canine larynx. It is an extension of a previous report (Alipour and Finnegan, 2013) with an emphasis on the gap between two false folds. The canine larynx was used due to its dimensional similarity and large ventricles. The results of this study indicate the following:

1. Widening of the ventricular gap resulted in an increased fundamental frequency, shorter glottal contact (decrease of closed quotient), more complex vocal fold vibration and increased acoustic spectral slope.
2. The midsagittal incision in canine epiglottis caused larger ventricular opening during oscillation with amplitude as high as 3 mm.
3. Dynamic widening of the ventricular folds results in an increased glottal flow, decreased subglottal pressure and shorter glottal contact.
4. The glottal flow resistance was larger for narrower gap.

5. The size of ventricular gap does not have significant effect of the sound pressure level.

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Figure 1.
Top view of the mounted canine larynx with a split in the epiglottis and sutures to control ventricular gap.

Figure 2. Glottal waveforms of an excised canine larynx #1 with neutral gap condition including electroglottograph (EGG), subglottal pressure (Ps), and Flow rate (Flow) with their corresponding kymographic image (top graph).

Figure 3.
Glottal waveforms of the same larynx at widened gap condition including signals similar to Figure 2.

Figure 4.
FFT spectra of EGG and microphone signals from the waveforms of Figure 2.

Figure 5.
FFT spectra of EGG and microphone signals from the waveforms of Figure 3.

Figure 6.
Calculated ventricular area and ventricular gap from high-speed images of a canine larynx oscillation at 122.8 Hz.

Figure 7.

Glottal waveforms during manual ventricular gap widening, including EGG, subglottal pressure, and Flow rate. Solid lines are for the narrow gap oscillations and dashed lines for wide gap oscillations.

Figure 8. Pressure-flow relationships of an excised canine larynx with three ventricular gaps of narrow (less than 1.2 mm), neutral (1.2- 2.5 mm), and wide (more than 2.5 mm).

Figure 9.

The average sound pressure level (SPL), fundamental frequency (Fo), and glottal flow resistance (GR) for seven canine larynges with three ventricular gaps of neutral, wide, and narrow. The values on the columns are mean and standard deviations

Table 1

Canine larynges with their oscillating conditions

Larynx	Gender	Weight kg	P _s cm H ₂ O	Flow ml/s	SPL dB	F0 Hz
1	F	21.0	7-36	590-1400	63-76	55-186
2	M	16.0	8-34	310-1400	63-81	69-112
3	M	20.0	8-34	280-1170	59-81	73-199
4	M	16.5	9-32	200-1400	59-82	68-170
5	M	21.0	8-28	190-1400	62-80	56-169
6	M	17.0	6-30	590-1400	61-83	80-183
7	M	15.5	8-30	620-1400	63-80	67-182
8	M	16.0	6-30	340-1400	61-79	94-204
9	M	16.0	5-35	450-1400	58-84	84-116