Ventricular pressures in phonating excised larynges

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Pressure in the laryngeal ventricle was measured with a beveled needle connected to a pressure transducer in excised canine larynges. Air pressures within the ventricle were obtained for different adduction levels of the true vocal folds (TVFs), false vocal folds (FVFs), and subglottal pressures (Ps). Results indicated that the air pressures in the ventricle appear to be strongly related to the motion of the FVFs rather than to the effects of TVF vibration. Both dc and ac pressures depend on FVF adduction, amplitude of motion of the FVFs, and whether the FVFs touch each other during the vibratory cycle. Mean and peak-to-peak pressures in the ventricle were as high as 65% of the mean and peak-to-peak Ps, respectively, when the FVFs vibrated with large amplitude and contact each cycle. If the glottis was not closed, a medial movement of the FVFs appeared to create a positive pressure pulse on the Ps signal due to an increase in the laryngeal flow resistance. The electroglottograph signal showed evidence of tissue contact for both the TVFs and the FVFs. The study suggests that the laryngeal ventricle acts as a relatively independent aero-acoustic chamber that depends primarily upon the motion of the FVFs.

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I. INTRODUCTION

The ventricular folds, also known as the false vocal folds (FVFs) or vestibular folds, are thick folds of tissue lying above the true vocal folds (TVFs), and separated from the TVFs by the laryngeal ventricle (or sinus of Morgagni). The laryngeal ventricle provides lubrication to the TVFs through mucous glands within the FVFs. The ventricle has been considered as an acoustic filter (Helmholtz resonator) by [Pepinsky \(1942\)](#), and a low-pass filter by [van den Berg \(1955\)](#). The observation that the shape and size of the ventricle changes during phonation has been reported by [Kitzing and Sonnesson \(1967\)](#) and [Agarwal et al. \(2003\)](#). The FVFs approximate during cough and swallow ([Pinho et al., 1999](#)), may be used in overtone singing as the sound source ([Lindestad et al. 2001](#)), can be used for voluntary rough low-pitched sounds ([Maryn et al. 2003](#)), and may have some linguistic significance in some languages.

During phonation, glottal flow passes by the ventricle as a pulsating jet and might influence the air pressures in the ventricle ([Hemon and Wojciechowski, 2006](#)), which, in turn, might affect the aerodynamic forces on the FVFs. In addition, during adduction of the TVFs, the FVFs may not be abducted out of the way and instead move toward the mid-line and initiate their own oscillation, which often is related to voice disorders when not voluntarily produced. On the other hand, the FVFs may be separated sufficiently far apart that they neither vibrate during TVF oscillation, nor interfere

with laryngeal aerodynamics by altering the laryngeal flow resistance ([Agarwal et al., 2003](#)). Also, when the FVFs vibrate, they may do so with or without touching each other. Thus, the FVFs can act in a non-interfering manner, alter the laryngeal flow resistance, or act as a second vibratory source of sound. The FVFs may vibrate when the TVFs do not, or both the TVFs and FVFs may vibrate simultaneously. In addition, the FVFs may vibrate at the same frequency as the TVFs, or more commonly at a lower frequency (often at the first subharmonic).

In the last decade few investigators studied the laryngeal models with false vocal folds to understand their acoustic or aerodynamic effects. These include static models, theoretical models, and excised larynx models. [Rosa et al. \(2003\)](#) simulated the vocal fold oscillations including false vocal folds and reported on the glottal waveforms with FVF dimensions as a parameter, but did not report any aerodynamic or acoustic effects associated with FVF.

The effects of FVF and ventricle on the sound source has been studied by some investigators using numerical models. For example, [Zhang et al. \(2002\)](#) assessed the influence of the FVFs on sound generation using computational fluid dynamics and concluded that the FVFs may impact voice production by reducing glottal flow resistance. In another theoretical study of the effects of the FVFs on the voice source, [McGowan and Howe \(2010\)](#) calculated the unsteady drag of vortices in a forced-oscillation model of the vocal folds and concluded that the FVFs do not have a noticeable effect on the voice source. In contrast, however, [Alipour et al. \(2007\)](#) and [Finnegan and Alipour \(2009\)](#) using excised canine larynges studied the aerodynamic and

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acoustic effects of the false vocal folds and determined that medial compression of the FVFs increased glottal flow resistance as well as sound intensity.

Kucinski *et al.* (2006) studied the airflow structures through a scaled-up static Plexiglas model of the larynx including false vocal folds using flow visualization. They found that flow in the glottis was laminar for all flow rates and all geometries they studied. They reported that a narrow FVF gap accelerated and straightened the glottal jet. On the other hand, a wide FVF gap behaved similar to the case with no FVFs. They showed a complex flow structure in the laryngeal ventricle (between the TVFs and FVFs), suggesting that the laryngeal ventricle may have important acoustic and aerodynamic effects.

Using similar static Plexiglas model, Agarwal (2004) performed extensive studies of FVF gaps, glottal diameters and angles, and translaryngeal pressures to determine the effects on laryngeal aerodynamics due to the presence of the FVFs. She reported a general equation that estimates the change of flow resistance depending on the relative diameters between the TVFs and the FVFs. A primary finding was that there was a range of FVF gap to TVF diameters between ~ 2 and 4, where the flow resistance is reduced by up to $\sim 25\%$, but for gaps less than one, flow resistance can be very large. Li *et al.* (2008) also studied the effects of the FVF gap using an experimental static Plexiglas model and a finite-element computational model. They found that glottal pressure was minimum and flow rate was maximum for the conditions for which the FVF gap was 1.5–2 times more than glottal gap. They also found that the presence of the FVFs moved the flow separation point downstream or made the glottal jet longer and smoother, suggesting acoustic efficiency.

Bailly *et al.* (2008) studied the aerodynamic interaction between the FVFs and the TVFs using an experimental setup with static and dynamic TVFs and fixed FVFs separated by a large and long ventricle. They also analyzed the aerodynamic effects of the FVFs using the Bernoulli equation. They concluded that the presence of the FVFs may have positive effects on the oscillation of the TVFs. In a later study, Bailly *et al.* (2010) investigated the effects of FVFs on the phonation of a singer during throat singing using direct laryngoscopy with high-speed imaging. Using kymographic images and estimates of the opening areas of the TVFs and FVFs, they reported that the FVFs closed once for every two closures of the TVFs with a phase difference.

Finally, Drechsel and Thomson (2008) studied the effects of supraglottic structure on the glottal jet. Using a self-oscillating synthetic model with rigid acrylic false vocal fold model and idealized straight tube vocal tract, they measured glottal jet with the particle image velocimetry and high-speed imaging. They concluded that the presence of the FVF in the vocal tract obstructed the starting of the downstream vortex. Also, they suggested that FVF decreased the root-mean-square values of the glottal jet and acted as a stabilizer in the vocal tract.

These studies, experimental and theoretical, have pointed to acoustic and aerodynamic effects of the laryngeal ventricle. However, the results of some of these studies may

be limited by the lack of pliable and moving false vocal folds. Particularly, accurate and reliable data on the pressures in the laryngeal ventricle that provide a driving force on both the true and false vocal folds are scarce. The air pressures within the ventricle may have a non-zero mean value as well as an oscillating component due to (a) the vibrating TVFs, (b) vortical structures due to the interaction of the glottal jet, FVFs, and the ventricular space, (c) resonance characteristics of the ventricular space, and (d) vocal tract input pressures. Thus, the ventricular space may affect the resulting acoustic pressures seen directly above the FVFs. The purpose of this study was to compare the ventricular pressures during vocal fold oscillations at different glottal configuration.

II. METHODS

Seven canine larynges were obtained following cardiovascular research experiments at the University of Iowa Hospitals and Clinics. Excised larynges were mounted and used according to previous work (Alipour *et al.*, 2007). Compressed air from the building was passed through a desiccant filter, in-line flow meter, heater, and humidifier and entered the larynx via a tapered 3/4 in. tubing (Fig. 1). As this study needed measures of pressure in the laryngeal ventricle, the supraglottic structures including the FVFs and the epiglottis were kept intact. Each excised larynx experiment started with pressure-flow sweeps at specific vocal fold adductions to evaluate the operating range of the larynx. Then, a series of sustained phonation runs were made within the working range of pressure and flow to record and observe oscillation of the vocal folds in slow motion visualized with a strobe light and with high-speed imaging for selected conditions. For a simultaneous view of the TVFs and the FVFs during phonation for three larynges (CL75, 76, and 77), the epiglottis was split along the mid-sagittal plane to create a wider FVF gap and sutured laterally out of the way. The gender, weight, and oscillating conditions of excised larynges are given in Table I.

For each sustained oscillation, five signals including electroglottograph (EGG), subglottal pressure, flow rate, microphone, and ventricular pressure were recorded. The

FIG. 1. (Color online) Schematic of airflow in the excised larynx setup.

TABLE I. Canine larynges with their oscillating conditions. PTP = phonation threshold pressure.

Larynx	Gender	Weight (kg)	PTP (cm H ₂ O)	F0 (Hz)
CL63	M	20	3.8 ± 1.0	158 ± 19
CL75	M	21	8.3 ± 2.9	98 ± 9
CL76	F	16	8.3 ± 0.6	134 ± 18
CL77	M	22	14.3 ± 1.5	149 ± 7
CL83	F	18	8.3 ± 3.0	141 ± 44
CL84	F	16	4.3 ± 0.5	162 ± 33
CL85	F	18	7.7 ± 1.5	118 ± 22
CL98	F	15	10.8 ± 4.2	85 ± 7

electrode plates from a Synchrovoice EGG, which were placed on the thyroid laminae, provided the EGG signal during phonation. The mean values of subglottal pressure and flow rate (controlled with a fine rotary valve) were read from a wall manometer and the in-line rotameter (Gilmont rotameter model J197). The subglottal pressure signal was recorded using a pressure transducer (Microswitch 136PC01G1, with an approximate bandwidth of 0–1 kHz) mounted perpendicular to the flow in the tracheal tube 10 cm below the TVFs with the end of the transducer near the tracheal wall. The flow rate was recorded with a pneumotach flow meter (Rudolph 4700) and low-range (0.88 cm H₂O) pressure transducer (Validyne DP103 with Diaphragm #8–10 and Carrier Demodulator CD15 from the same company) upstream of the humidifier (ConchaTherm® unit, RCI Laboratories). This signal provided the time varying flow rate, but due to the distance and humidifier in its path (see Fig. 1), the signal was low-pass filtered and was not used as an indication of the instantaneous glottal flow. The audio signal was obtained with a microphone (Sony ECM-MS907) placed at a distance of 15–20 cm from the larynx and recorded on a digital audio tape recorder (Sony PCM-M1). The tubing distance from the TVFs to the ConchaTherm was 48 in., suggesting a subglottal resonance of ~135 Hz (for a closed–closed duct system).

The ventricular pressure was measured with another transducer of the same type as the subglottal pressure. The transducer was attached to a disposable hypodermic needle (16 gauge, 1.5 in. long) via a custom-made adaptor. The needle was inserted externally from a posterior location, lateral to the right arytenoid, parallel to vocal fold surface while observing its insertion from above by opening the ventricle using a thin wooden stick; the needle was placed against the lateral wall of the ventricle with the open beveled tip facing the midline (see Fig. 2). A wire was passed through the needle before each run to assure its clearance. After needle insertion, the transducer was attached to the needle with the adaptor.

Adduction of the TVF was controlled by a pair of sutures pulling on the muscular process of each arytenoid cartilage to simulate lateral cricoarytenoid and (lateral) thyroarytenoid muscle action, as in arytenoid adduction. The adduction levels were the weights (50–200 g) that pulled the sutures attached to the muscular processes. In two larynges (CL76 and CL77), when there was not enough glottal flow resistance to initiate phonation, a suture was used to bind the

FIG. 2. (Color online) (A) Mounted excised larynx with split epiglottis and pressure probe. (B) Hemilarynx cut view of the ventricle and pressure probe (hypodermic needle).

arytenoids together to close the gap (to simulate the intra-arytenoid muscle contraction). The FVF was medialized and lateralized manually using a pair of tweezers for some larynges.

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 into a computer using an analog-to-digital (14 bit) board and software (DATAQ Instruments). The signals were then converted to calibrated physical quantities in a MATLAB routine and used for the aerodynamic and acoustic analyses.

Spectral analyses of the signals were obtained with a fast Fourier transform (FFT) of the microphone signal in the MATLAB computing environment. Each FFT was calculated with at least 4096 data points for adequate resolution. To calculate the fundamental frequency (F0), the EGG signal was low-pass filtered at 150% of its estimated F0 value seen from the spectrogram or an oscilloscope. The fundamental frequency was then calculated with a zero crossing method. First the signal's dc offset was removed and then the periods of all the cycles in the selected segment were calculated from consecutive zero crossings and averaged. In some high-jittered cases, the upstream flow signal was used to extract F0 similarly.

High-speed imaging was performed with a monochrome camera (Photron, model 100K Fastcam-X 1024 PCI). For selected cases, the larynx was illuminated with a Lowell Pro light at a distance of ~50 cm and video images were acquired during oscillations at a rate of 5000–10 000 frames/s for a short duration (1–2 s) due to the memory limitations and to avoid damage to the vocal fold tissues by the intense light. For each video capture, 500 frames of the video image were

downloaded from memory to disk for later analysis. This number of frames provided images for five to ten oscillation cycles in order to compare TVF and FVF oscillations and its download time was less than a minute, which was reasonable during experiment. The recorded frames were later converted to kymographic images in MATLAB using custom-made software. Due to the heat of the light that could damage the larynx, only two to three video images were acquired for each sustained oscillation and pressure flow sweeps that were ~ 20 s were not captured by high-speed video.

The frames of high-speed video during sustained oscillations with FVF vibration can be processed in image processing toolbox of MATLAB package for ventricular gap measurement. By manually and interactively selecting a gray threshold value, the ventricular opening can be converted to black spot and minor axis of these spots can be measured as ventricular width or gap while frames are advanced. This time-consuming process was performed for one larynx and results were reported later.

III. RESULTS

Figure 3 shows frames of the high-speed video for excised larynx CL83, which was oscillating 87.2 Hz with subglottal pressure of 20 cm H₂O and captured at 10 000 frames/s. These frames are shown with an interval of 0.6 ms and cover approximately one cycle of the oscillation. The sequence of frames is from the top to bottom and then left to right, and starts from the widest FVF gap. The true vocal folds are partially visible in some frames with darker shadow, but not viewable in most cases because of the narrow epiglottal tube in the canine larynx and the position of the camera (40 cm above the larynx), which at best could see partial views of the true vocal folds.

The technique of setting the prephonatory conditions and then increasing flow to “sweep” from a low subglottal pressure to a high subglottal pressure resulted in some cases

FIG. 3. Frames of a high-speed video for larynx CL83 captured at 10 000 frames/s demonstrating oscillations of the true and false vocal fold during a cycle. Sequence runs from the top to bottom and then from left to right. The horizontal axis corresponds with anterior-posterior direction.

of starting phonation with only the TVFs vibrating, and then subsequently having the FVFs begin to vibrate. Such sweeps typically resulted in an increase in the F₀ when the TVFs only were vibrating, as has been reported in earlier studies (Alipour *et al.*, 2007), but typically *without* F₀ increase when the FVFs vibrated. This is illustrated in Fig. 4 for larynx CL85, where F₀ increased during TVF vibration to the 6 s mark, followed by a transition for ~ 1 s, and then with a lower F₀ that tended to decrease starting at ~ 7.2 s when the FVFs were dominant in the vibration. The FVFs were moving with a relatively large mucosal wave at the higher pressures as observed from stroboscopic video. The amplitude of the EGG waveform (Fig. 4, second panel) also indicates a significant increase in contact tissue area around the 6 s mark, as the FVFs began to oscillate and collide. In addition, the spectrogram of the microphone signal clearly illustrates the TVF, transition, and FVF dominance (Fig. 5, top graph; time was reset from the start of oscillation). These spectrograms were made in MATLAB with a window size of 4096 points and a window type of Blackman Harris. Thus, this case illustrates the possibility of FVF inclusion into laryngeal phonation for higher pressures, the consequent change of the output spectra with a lower F₀ and strong initial partials, and suggests that the EGG signal reflects both TVF and FVF tissue contact.

A more extreme case of transition from TVF to FVF vibration is illustrated in the spectrogram of Fig. 5 bottom graph. For this case, only TVF vibration is evident for the first 4 s, followed by large amplitude of motion of the FVFs

FIG. 4. (Color online) Pressure-flow sweep in excised larynx CL85. The graphs from top to bottom include mean subglottal pressure (Ps), EGG amplitude, fundamental frequency, and mean ventricular pressure.

FIG. 5. (Color online) Spectrogram of the excised larynges CL85 (top) and CL76 (bottom) during sweep.

without touching (from 4 to 6s), where a lower frequency (about an octave) is produced, followed by a very rough sound, where oscillation of the FVFs was highly irregular (but again the FVFs were not seen to touch). This case indicates that the FVFs need not touch to be highly influential in the output spectral characteristics, creating either a relatively harmonic signal or a highly inharmonic signal. The existence of the additional partials in spectrum may have been caused by some other phenomena such as aerodynamic or acoustic, however our video stroboscopic observation confirms our assessment.

Typically the pressure in the ventricle increases throughout the sweep, that is, as subglottal pressure and flow increase. This is illustrated in Fig. 6 for seven larynges, including split epiglottis larynges (hollow symbols) and intact epiglottis (solid symbols); where their maximum ventricular pressure is plotted against their subglottal pressure. It appears that the split epiglottis group has lower pressures due to the larger ventricular opening and gap. A linear regression reveals that the split epiglottis group (thick dashed line) has a much lower slope of 0.28 compared to the intact group (thick solid line) with slope of 0.78. This suggests that the maximum ventricular pressure for the intact epiglottis can reach up to a maximum of 78% of the subglottal pressure. For some larynges, the sweep produced an increase in the volume of the ventricle, seen as an expansion of the external surface of the larynx (the structure “puffed up” as shown with arrow in Fig. 7). This might be due to “trapping” air in the ventricle with greater flow through the larynx. That is, the glottal jet not only would create presumed circulating airflow within the shunt ventricles, but

FIG. 6. (Color online) Maximum ventricular pressure in excised larynges as a function of subglottal pressure at medium adduction level. The solid line is the linear regression fit for the narrow FVF gap (NGfit) with the slope of 0.78 and the dashed line is the linear regression fit for the wide FVF gap (WGfit) with the slope of 0.28.

FIG. 7. (Color online) Superior view of an excised larynx before (top) and after (bottom) pressure-flow sweep. The external surface (marked with an arrow) is puffed up after the sweep.

also would impound air pressure to expand the ventricle. This would alter both the circulatory characteristics as well as resonance characteristics of the ventricle (neither directly studied here).

Figure 8 shows three cycles of waveforms in the canine larynx (CL98) with false folds oscillations; including EGG, subglottal pressure (Ps), ventricular width (maximum opening gap), and ventricular pressure (Pv). The larynx oscillated at a frequency of 88.5 Hz with a mean subglottal pressure of 20 cm H₂O. The examination of the video kymograph indicated that the true vocal folds had low amplitude oscillation, but the false vocal folds had large amplitude oscillation with contact at the same frequency of the true vocal folds. The ventricular width or gap was obtained from the high-speed images of the larynx CL98 for 9 consecutive sustained oscillations (runs) at various subglottal pressures. This process provided a waveform of the ventricular gap (a value for every 50 ms) that is compared to the ventricular pressure waveform. To combine this waveform with EGG and pressure waveforms, it was assumed that the minimum width (when the tissues are closest) corresponds to the maximum EGG signal. In this arrangement, ventricular pressure was maximum when the false folds came together and minimum when they were far apart. The ventricular gap varied between 0 and ~7 mm, indicating large amplitudes of oscillation.

The examination of video kymography from excised larynges suggests that the FVFs may vibrate at the same frequency as the TVFs, including low frequency modulations,

FIG. 8. (Color online) Instantaneous ventricular pressure (Pv), ventricular width (VW) along with subglottal pressure (Ps) and EGG signal for the excised larynges CL98.

or at a lower frequency. The subglottal and ventricular pressures reflect these motions. These findings will be demonstrated in the following figures. Video kymography was used to help show the relation between the TVF and FVF vibration and phase timing. The images show FVF motion overlaying TVF motion at particular coronal locations.

Figure 9 shows an example of a case for larynx CL75, where neither the TVFs nor the FVFs touch but both oscillate at the same frequency (adduction was 50 g). In Fig. 9 a kymographic display calculated at 27% of the length from posterior (top panel) for 50 ms, but not synchronized with other signals shows the TVFs approximating maximally before the FVFs approximate maximally, and neither the TVFs nor the FVFs touch. The first signal panel below the kymograph shows a double pulsing of the Ps signal, and below that a double pulsing of the microphone signal in synch with the Ps signal relative to the spacing between the local maxima. The last panel is of the ventricular pressure Pv, showing only a single pulse. It is suggested, because of the timing of the TVF and FVF movement in the kymograph, that the first pulse of the Ps and Mic signals was due to the approximation of the TVFs, and the second pulse of the Ps and Mic signals was due to the approximation of the FVFs, and the Pv pulse was due only to the movement of the FVFs. The lack of a second pulse of pressure in the ventricle suggests that the ventricle did not sense the acoustic result of the TVF approximation. It is important to indicate that in this case the glottis and FVF gap never reached zero, so that

FIG. 9. (Color online) Kymograph image calculated at 27% of the length from posterior (top panel) and glottal waveforms of the excised larynx CL75 at low adduction phonation including subglottal pressure (second panel), microphone (third panel), and ventricular pressure (fourth panel). In the top panel, the false vocal folds (lighter teeth) partially cover the true vocal folds (darker teeth).

the subglottal region would have been able to sense all changes in laryngeal flow resistance at any airway location.

A different case from the same larynx (CL75) with greater adduction (150 g) is seen in Fig. 10. The kymograph shows partial closure for both the TVFs and the FVFs, again with the same frequency of oscillation and similar phasing as in Fig. 9. The panels below the kymograph now include the EGG signal (it was not available for the previous figure) and demonstrate an important finding, that of showing EGG pulses essentially separately for collision of the TVFs and then for collision of the FVFs (this inference suggests that the EGG indeed combines effects from both the TVFs and FVFs when both occur together, or separately if the contact is sufficient and separated in time). The Pv pressure pulse corresponded in time to FVF collision and the second EGG pulse. Again the ventricle appears to have been insensitive to the primary acoustic excitation relative to TVF collision.

These cases suggest that the air pressure changes in the ventricle are sensitive to the position of the FVFs but minimally to TVF glottal activity, that the subglottal pressure will register increased air pressure when the FVFs approximate if there is lack of closure of the TVFs, and that the EGG signal reflects contact of both the TVFs and FVFs.

The ventricle as an airway acoustic shunt may register different spectra inside the ventricle from the spectra of the signal recorded by the microphone system. Figure 11 is for larynx CL77 in which the FVFs were held laterally by

FIG. 10. (Color online) Kymograph image calculated at 46% of the length from posterior (top panel) and glottal waveforms of the excised larynx CL75 at high adduction phonation including EGG (second panel), subglottal pressure (third panel), microphone (fourth panel), and ventricular pressure (fifth panel). In the top panel, the false vocal folds (lighter teeth) partially cover the true vocal folds (darker teeth).

FIG. 11. (Color online) FFT spectrum of microphone (top panel) and ventricular pressure (bottom panel) for excised larynx CL77.

tweezers, creating little ventricle effect. Figure 11 shows the spectrum for the Mic signal at the top and for the Pv signal at the bottom. The fundamental frequency and second harmonic were registered in the ventricle, with little harmonic energy above that. The spectrum of the Mic signal shows a slightly higher second partial than the first. It is pointed out that the highest harmonic of the Mic signal can be the first harmonic (found in certain runs of this study but not reported here), but can also be the second harmonic for the excised canine larynges (Alipour *et al.*, 2012).

In contrast, Fig. 12 indicates that there was a subharmonic to the TVF oscillation found in the Pv signal (lower trace), as well as numerous spectral components of the Mic signal strongly in the Pv signal. Here the adduction was low, but the FVFs came together strongly (larynx CL85). This case is of interest also because of the noise content on the signals. There is less noise shown in the Pv signal spectrum than in the Mic signal spectrum. The turbulence from the glottal flow may not have developed sufficiently at the spatial location of the ventricle (where the laminar core of the jet may have been maintained) as it would have after moving past the medial surface of the FVFs, and may not have radiated backward toward and into the ventricle. These spectral results suggest that the movement of the FVFs may act to significantly affect the acoustic signal that reaches a nearby microphone and is perceived by the listener.

IV. DISCUSSION

This study examined some effects of the presence of the FVFs during phonation of the excised canine larynx. Although the canine larynx is not identical to the human

FIG. 12. (Color online) FFT spectrum of microphone (top panel) and ventricular pressure (bottom panel) for excised larynx CL85.

larynx, some similarities exist from the geometric, structural, and dimensional point of view. Thus, the general effects of the presence of the FVFs may be sufficiently similar to the human situation to warrant the results here as hypotheses to be tested in humans.

A. Ventricular aerodynamics

The transglottal pressure is the pressure drop between the subglottal region and just above the glottis, upstream of the FVFs, meaning essentially at the level of the laryngeal ventricles. If the pressure were uniform across the airway, the ventricular pressure would be the pressure just above the glottis used to drive the air through the glottis, as well as set up a pressure differential on the vocal fold tissue to drive the tissue vertically. This reasoning suggests that when the ventricular pressure is positive, there would be less transglottal pressure and less vertical force on the vocal folds. This finding is supported by static physical modeling by [Agarwal et al. \(2003\)](#).

The acoustic pressures within the ventricle appear to depend on the relative FVF gap as was shown in Fig. 6. If the FVFs are relatively far apart and not vibrating, the space above the glottis is fully exposed to the supraglottal region “without interference,” and thus the supraglottal pressure should not be affected by the FVFs and the ventricles. That is, in this case the ventricles essentially receive no flow but just exist as a diminished lateral space, and are most likely not highly excited relative to resonance. As the FVF gap narrows, the ventricle may take on greater volume and receive airflow from the glottis because the FVF medial edges would be closer to the glottal jet.

The pressures within the ventricle during FVF vibration consist of both dc and ac pressures, both of which tend to rise as subglottal pressure increases when the FVF gap allows air to enter the ventricle. The air pressure tends to pulse strongly within the ventricle when the FVFs have large amplitudes of motion and contact each other during the vibratory cycle. These pulsations (the ac pressure variations) appear to be controlled more by the FVF movement than by the signal from the TVF oscillation. Thus, despite the different lowest natural frequencies of the TVFs and FVFs, the FVFs may synch with the TVFs, but the ventricle itself acts as a relatively independent aero-acoustic chamber the features of which depend upon the actual motion of the FVFs.

The pressure within the ventricle was nearly always positive for the cases studied, and with FVF closure during the cycle could become $\sim 65\%$ of the P_s values. It is noted that there was no vocal tract attached superiorly to the larynxes. It is reasonable to expect that had a vocal tract been attached, the inertance of the tract would have created rarefaction pressures above the glottis and greatly influenced the pressures in the ventricle. It is doubtful that the ac pressure extents would have disappeared, assuming they are due to the FVF vibration, but the dc pressures may have shifted accordingly. This would shift the bias of many of the ac ventricular pressure waveforms. The consequences may be the inclusion of negative pressures within the ventricle and less consequential dynamic extension (distension) of the ventricle volume. The effects of the presence of the vocal tract on the ventricular pressures need to be studied.

B. Clinically related issues

Although voluntary vibration of the FVFs is a relatively easy function to perform, plica ventricularis is a phonatory disorder involving the non-voluntary vibration of the FVFs to create the phonatory sound source, often as an alternative or compensation to TVF phonation ([Stager et al., 2000](#)). The study here directly investigated consequences of such FVF vibrations. The findings here suggest that, if the FVFs are positioned in such a way that they may be placed into vibration, increasing subglottal pressure and flow may set them into motion (they typically would not begin vibrating in this study until subglottal pressures were above 10 cm H₂O). An obvious implication is that lateralizing the FVFs would reduce the tendency for the FVFs to vibrate, which voice therapy attempts to accomplish.

Although this project did not study the effect of the presence of the FVFs on the vibration of the TVFs *per se*, potential change in laryngeal flow resistance would affect the intraglottal pressures and thus the forcing function on the vocal folds. In addition, the positive mean ventricular pressures measured in this study when the FVFs were in oscillation suggest that air pressure pushes onto the top of the vocal folds, creating a potential inhibition of more lateral vocal fold tissue motion.

In addition, the motion of the FVFs, even if they do not touch, appears to affect the microphone signal (and subglottal pressure signal) by literally valving the glottal flow in a grossly similar manner to that performed by the TVFs. This

appears to result in altering the intensity of the lower partials, from adding a subharmonic (and its overtones) to the output signal, to shaping the first five partials depending upon the presence of modulations of the TVF and FVF cycles, to creating a highly inharmonic signal that has an extreme rough quality. These FVF-related acoustic changes should alter the sound quality related to the lower frequencies, especially near the first vocal tract resonance. Perceptual studies of the various effects need to be performed.

A laryngocele is an abnormal swelling of the ventricle (Dray *et al.*, 2000), a phenomenon inferred in this study in some larynges during the pressure-flow sweeps. This enlargement of the ventricle is associated with increased dc and ac pressures in the ventricle, and therefore potentially increasing the vertical air pressure on the TVFs and possibly increasing the glottal flow resistance more than if the FVFs were absent.

The pressure-flow sweeps indicated that F0 can be readily changed with this technique, but the F0 of the FVF vibration is much reduced in comparison, suggesting that the F0 range for ventricular phonation would be found to be restricted in a patient.

The clinical (as well as pedagogical) usefulness of the EGG signal was fortuitously emphasized in some examples of this study, namely that the signal does indeed appear to register tissue contact for both the TVFs and the FVFs. If there is a timing difference between contact of the TVFs and FVFs, the EGG signal may reveal this timing difference by appearing as separate EGG pulses or as atypical EGG waveforms. This would have diagnostic importance relative to predicting that the FVFs were in vibration, and the timing of FVF collision relative to TVF collision.

C. Theoretical note

The acoustic sound source in speech has been taken to be that occurring just above the glottis. It is apparent that the FVFs can affect this sound source in the “near field” of the glottis (through glottal jet guidance, dipole sound source generation at the medial FVF edges, and potential inhibition of lateral vocal fold vertical motion), and can contribute to this sound source if the FVFs are vibrating (adding components relative to the motion of the FVFs themselves, and filtering at higher frequencies). The *laryngeal sound source*, then, should be considered to be the *supra-ventricular aero-acoustic consequence of the dynamic double orifice of the TVFs and FVFs*. This would be the excitation signal to the laryngeal tube and vocal tract.

V. CONCLUSIONS

This study examined air pressures within the laryngeal ventricle for the phonating larynx. The excised canine model was used. A bevel-tip hypodermic needle was placed in the lateral ventricular space while connected externally to a broadband pressure transducer. Numerous larynges, adductions, and subglottal pressures created a wide range of conditions to explore aerodynamic and acoustic effects of the FVFs and the pressures within the ventricle.

Primary results from this study include the following:

- (1) In the canine model, the FVFs tend to vibrate at higher pressures if the FVFs are close enough, thus making this a good model for the study of ventricular pressures and general effects of vibrating FVFs.
- (2) FVF vibration may vibrate in-phase with the TVFs, out-of-phase with the TVFs, or at a subharmonic to the TVF vibration. The study was insufficiently parametric to discover the underlying causes of these differences.
- (3) The pressures in the ventricle were positive in this study, but the setup lacked the vocal tract, which would most likely have altered the ac pressures to include negative values.
- (4) The acoustic pressure effects of vibrating FVFs can be seen on the subglottal pressure signal if the glottis does not completely close (as would be the case in breathy phonation). An inward movement of the FVFs appears to create a positive pressure pulse on the Ps signal due to an increase in the laryngeal flow resistance (as well as a positive pressure pulse within the ventricle).
- (5) Typically the spectrum of the ventricular pressures included components related to both the motion of the FVFs as well as the TVF-generated spectrum.
- (6) The EGG signal appears to include the “contact area” for both the TVFs and the FVFs.

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