ASYMMETRIC AND SYMMETRIC VOCAL FOLD OSCILLATION IN THE EXCISED SQUIRREL MONKEY LARYNX

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Abstract: The larynges of nine squirrel monkeys were harvested, dissected, mounted on a tapered pseudotracheal tube, and phonated using heated and humidified air. The patterns of oscillation of the vocal folds were videotaped with stroboscopic illumination, and simultaneous measurements of airflow, subglottal pressure, and audio signal were obtained. The pressure wave and audio signal were subjected to spectral and phase portrait analysis methods. It was found that the left vocal fold tended to oscillate at lower subglottal pressure compared to the right vocal fold. This resulted in unilateral oscillation. Bilateral oscillation was seen at higher subglottal pressures. Patterns of symmetric and asymmetric bilateral oscillations were observed.

I. INTRODUCTION

The squirrel monkey larynx exhibits at least four different regimes of oscillation including biphonation, staccato phonation, and aperiodic phonation, as well as periodic phonation with overtones [1]. These various regimes of oscillation are exhibited “naturally” in the excised squirrel monkey larynx without any attempt to manipulate differentially the stiffness, mass, or elongation of the left and right vocal folds. In the present study we examined selected cases from our data set in which bifurcations between symmetric and asymmetric patterns of vocal fold oscillation were observed as a function of changes in subglottal pressure, while vocal fold elongation and adduction were held constant. Of particular concern here is the observation that as subglottal pressure is incremented and the threshold for phonation is achieved, the pattern of vocal fold oscillation is frequently unilateral, the right vocal fold is relatively immobile and oscillation is nearly confined to the left vocal fold. It is as if the mechanical properties of the left and right vocal folds differ with the right vocal fold exhibiting greater stiffness. At other levels of subglottal pressure bilateral motion of the two folds is observed, and the bilateral oscillations may be either synchronized or asynchronized. The goal of the present study was to examine the acoustic significance of transitions between asymmetric and symmetric patterns of oscillation.

II. METHODOLOGY

Subjects: Excised squirrel monkey larynges were obtained from the Squirrel Monkey Breeding and Research Resource, University of South Alabama. The Squirrel Monkey Breeding and Research Resource, housing approximately 500 animals, is the largest squirrel monkey colony in the United States, with a low annual mortality of about 5%. The larynges of nine monkeys were harvested from animals which suffered a natural spontaneous death. No monkeys were killed for the purpose of conducting this research. Larynx ID 1630, 4510, 90780 and 2618 were extracted from adult female Bolivian squirrel monkeys (Saimiri boliviensis boliviensis). Larynx ID 1232 was removed from an adult female Guyanese squirrel monkey (Saimiri sciureus sciureus). The remaining three larynges were harvested from the Peruvian subspecies (Saimiri boliviensis peruviensis). Of these, Larynx ID 410 was harvested from an adult male, while larynx ID 742 and 9004 were obtained from adult female specimens.

Figure 1: Mounted larynx with control sutures.

Apparatus and Procedure: Experiments were conducted in an IAC single-walled both in which the
interior surfaces were covered with Sonex foam to reduce acoustic reflections. Each larynx was dissected and trimmed, and the false vocal folds were removed. The tracheal tissue and larynx was mounted on a pseudotracheal tapered rigid tube (3mm average diameter), positioned on a laboratory bench, and the tracheal axis was oriented in the vertical position, exposing the glottis to a camera and recording apparatus. Adduction was controlled by two sutures attached to micrometers which pulled together the arytenoid cartilages. In one condition, the length of the vocal folds was not manipulated, and the larynx was permitted to phonate freely without any attachments to the thyroid tissue. In the second condition, vocal fold length was manipulated. A surgical suture pulling the thyroid cartilage against the cricoid cartilage controlled the length changes. No attempt was made to apply asymmetrical adjustments to differentially lengthen the left and right vocal folds. Figure 1 shows a squirrel monkey larynx mounted on the pseudotracheal tube.

The pseudotracheal tube received air from the building's oil and water free compressed air supply. The air was heated to 37° C via a Concha Therm III Servo Control Heater (RCI laboratories, Arlington Heights, IL), and was humidified to approximately 100% relative humidity. The mean air pressure below the glottis was monitored with a wall-mounted water manometer (Dwyer No. 1230-8), and the mean flow rate was monitored with an in-line flowmeter (Gilmont rotameter model J97). The top view of the larynx and vocal folds was videotaped (Sony model DC-102) for later image analysis, and for stroboscopic images, a Pioneer DS-303ST stroboscope was employed. The audio recordings of the signal were obtained with an Shure (model 48) microphone also positioned 10 cm above the glottis, the analog signals were recorded on a Sony model PC-108M Digital Audio Tape (DAT) recorder, and simultaneously filtered, sampled, digitized (12-bit A/D, 44.2 kHz sample rate) and stored on a Gateway personal computer. The digitized time series data were analyzed with MATLAB or TFR signal processing software.

III. RESULTS

Each larynx was readily phonated, and each larynx exhibited samples of both stable phonation, and samples of irregular phonation characterized by nonlinear phenomena. In the present study we kept subglottal pressure to 40 cm-H_2O or less. In this preparation, variations in subglottal pressure of 40 cm H2O or less produce fluctuations in the amplitude of voicing that matches the range in amplitude of vocalizations recorded from nonhuman primates [1]. Summed across all nine larynges we recorded 546 samples of phonation.

At the onset of phonation over half of the samples exhibited unilateral phonation where oscillation was virtually confined to the left vocal fold and the right vocal fold was nearly immobile. As subglottal pressure was incremented, airflow increased and motion in the right vocal fold was initiated. We did not encounter examples were unilateral oscillation was observed in the right vocal fold, and the left vocal fold was nearly stationary. Figure 2 shows the audio waveform FFT for larynx ID 2618 at subglottal pressures of 29 and 39 cm-H_2O respectively. At a subglottal pressure of 29 cm-H_2O oscillation was nearly unilateral with good oscillation in the left vocal fold and very little motion in the right vocal fold. At a subglottal pressure of 39 cm-H_2O, synchronized bilateral oscillation was observed. The amplitude of the second harmonic increased markedly when bilateral oscillation was established.

Figure 2: A (top panel) FFT of a unilateral oscillation, B (bottom panel) FFT of a synchronized bilateral oscillation.

Figure 3 shows a similar example of this phenomenon for larynx ID 2683. At a subglottal pressure of 23 cm-H_2O oscillation was unilateral, and synchronized bilateral oscillation of the vocal folds was observed at a subglottal pressure of 32 cm-H_2O. At intermediate subglottal pressures this larynx exhibited bilateral oscillation, but the left and right folds oscillated out of phase with one fold “closing” as the other fold was “opening”. In Figure 3 bilateral phase shifted oscillation is shown for a subglottal
pressure of 24 cm-H2O. As was observed in Figure 2, synchronized bilateral oscillation was associated with a prominent second harmonic of the fundamental frequency, and a third and fourth harmonics were also evident.

![Figure 3](image1.png)

**Figure 3:** A (top panel) FFT of unilateral oscillation, B (middle panel) FFT of a bilateral phase shifted oscillation, C (bottom panel) FFT of bilateral synchronized oscillation.

These findings suggest that in the squirrel monkey the vibrations in the tissue in the left half of the larynx are not strongly coupled to those in the right side of the larynx, and this increases the possibility that different frequencies or modes of oscillation may be established simultaneously within the laryngeal complex. Figure 4 shows the waveform recorded from a pressure transducer, the FFT of this waveform and the phase portrait of this waveform for complex bilateral oscillation for larynx ID 1232. In this case the vibration patterns in the left and right vocal folds were not synchronized or coupled with each other. This is shown by the fact that the frequency peaks in the FFT were not harmonically related, and the phase portrait was elliptical.

![Figure 4](image2.png)

**Figure 4:** A (top panel) FFT of a low-pass filtered pressure signal measured 2 inches below the vocal folds during asymmetrical bilateral oscillation, B (bottom panel) phase portrait for the above case. The x-axis displays the position of the signal, the y-axis the derivative.

**IV. DISCUSSION**

In three previous studies that focused on the nonlinear behavior of vocal fold vibration, nonlinear behavior was experimentally induced by asymmetrically manipulating the stiffness of the two vocal folds [2,3], or the tension and length of the two folds [4]. Berry and his colleagues noted that only occasionally were asymmetric patterns of oscillation observed for symmetric folds [4]. In contrast, in the present study, several patterns of asymmetric oscillation were observed, and these phenomena occurred readily without any experimental manipulation to induce asymmetries in the stiffness,
length or tension of the vocal folds. These observations are consistent with the idea that the magnitude of the coupling between the left and right vocal folds may differ prominently between species, and anatomical studies may help elucidate the differences between the laryngeal tissues of species that exhibit lax or tight coupling.

The present findings were also consistent with the idea that the membrane characteristics of the left and right vocal fold differed such that the right vocal fold exhibited functionally greater mass or stiffness compared to the left fold. Unilateral oscillation was almost entirely confined to the left vocal fold, and symmetrical bilateral oscillation tended to require greater airflow and subglottal pressures. Careful anatomical studies may reveal left-right asymmetries in the tissue complex that may account for this phenomenon.

As shown by Giovanni, Ouaknine, Guelfucci, Yu, Zanaret, and Triglia, if the two vocal folds differed in their relative stiffness, then the frequency and amplitudes of oscillation of the vocal folds would differ, and could result in a signal characterized by the nonlinear phenomenon of an asymmetric attractor [3]. In this case the amplitude of the signal should wax and wane according to the nonlinear combination of the oscillations of the two folds. These mechanisms may account for the characteristics of the sample shown in Figure 4.

V. CONCLUSION

The data suggest that the mechanical properties of the left and right vocal fold differ with the right vocal fold exhibiting greater stiffness. The data also suggest that the coupling between the left and right vocal folds is comparatively weak in the squirrel monkey. The left vocal fold tends to oscillate with greater amplitudes and at lower subglottal pressures compared to that observed for the right vocal fold. These phenomena result in unilateral and bilateral patterns of oscillation of the vocal fold. In some cases the absence of coupling results in asymmetric patterns of bilateral oscillations.

REFERENCES


