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5aSCa2. Relationship between divergence angle and skewing of the volumetric flow rate in an excised canine larynx model without a vocal tract
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Until now, skewing of the volumetric flow rate (Q) curve was thought to be due to the inertance effects produced by the vocal tract. The goal of these experiments is to measure the volumetric flow rate at the entrance and exit of the glottis during the closing phase in a 1mm thick coronal section halfway between the anterior commissure and the vocal process. The velocity fields and the intraglottal geometry are measured using modified particle imagining velocimetry (PIV) methodology. In these experiments, 1 excised canine larynx was used, and in all of them it is shown that the flow rate is greater at the glottal exit than at the glottal entrance when the glottis is divergent and an intraglottal vortex is formed at the superior aspect of the fold. In addition flow skewing is seen at the glottal exit but not at the glottal entrance. In this talk we will show that this flow skewing without a vocal tract is due to the entrainment effects of the intraglottal vortex.

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INTRODUCTION

In the standard source filter theory, the source of sound is due to flow modulation (Fant, 1960). While the flow is changing, or being modulated throughout the opening and closing phases of vocal fold vibration, it is though that the majority of sound is produced during the period when the flow rapidly decreases. The maximum flow deceleration rate is known as the MFDR and is thought to be significant factor in determining acoustic intensity and the amount of acoustic energy in the higher frequency harmonics (Stevens, 2000). The phenomenon of flow decreasing at a much more rapid rate than it increases is known as flow skewing. In the classic two mass models, this flow skewing is found to be due to the inertance of the vocal tract (e.g. Titze, 1988); however this conclusion has not been tested in a tissue model. The closest experimental measurements were made by Verneuil et al (2003), which used hot wire anemometry to measure velocities 1 cm above the folds in three anterior posterior locations. Area between the folds was determined from imaging, and the values of area and velocity were used to determine flow rate. Although this was an impressive first approximation of the actual flow rate at the glottal exit, there were two major limitations. The first is that 1 dimensional hot wire anemometry assumes that velocity is only in one direction; Khosla et al () showed significant velocity fields in all three dimensions one cm above the glottal exit in excised canine larynges. The second is that the methodology described in Verneuil et al (2003) assumes the velocity fields 1 cm above the folds is similar to the velocity field at the glottal exit; Khosla et al (2007) showed that is not completely accurate by measuring velocity fields above the glottal exit for excised canine larynges.

In this paper we present methodology for measuring flow rate at the glottal exit for a 1 mm thick (in the anterior-posterior direction) cross section at the mid-membranous location of the glottis. The excised canine larynx is used. This is also an approximation, but as will be described in the discussion section, there are good arguments to be made that our measured flow rate is qualitatively similar to the actual flow rate. Specifically we are looking to see if flow skewing occurs without a vocal tract, and if so what is the mechanism; both of these can be done by looking at a thin cross-section.

METHODOLOGY

One excised larynx was harvested from shared research mongrel canines immediately after the animals were euthanized. All cartilage and soft tissue above the vocal folds were removed, producing an unobstructed view of the vocal folds. A suture was used to adduct the vocal processes, and was tied with the minimal tension needed to have a prephonatory width of 0 mm between the vocal processes. Special care was taken to position the suture symmetrically in both the anterior-posterior and inferior-superior directions. The posterior gap, which is much larger in canine larynges than in humans, was also closed with stitches

The larynges were held in space using four prongs attached to the cricoid. An anterior stitch was placed around the inferior midline of the thyroid cartilage to simulate the cricothyroid muscle and to lengthen the fold. For each larynx, the stitch was adjusted and set at the amount of tension that gave the highest SPL for subglottal pressures just above the phonation threshold pressure. The trachea was fitted over an aerodynamic nozzle that was designed to minimize turbulence and produce flow with a consistent velocity profile. The airflow entering the nozzle was controlled and measured using a coriolis flow meter (Micro Motion, CMF025, Boulder CO), a pressure regulator (ControlAir Inc, Model 700, Amherst NH), and a mass flow controller (Parker, MPC 251, Cleveland OH). Static pressure measurements were taken at the nozzle using a pressure transducer (Honeywell, PFG, Golden Valley MN). In order to seed the flow, an atomizer was used (TSI, model 9306, Shoreview MN) using DEHS oil (Bis(2-ethylhexyl) sebacate, Alfa Aesar, Ward Hill, MA).

The PIV images were collected by illuminating the flow using a high repetition rate, dual cavity, Nd:YLF laser system (Litron, LDY304, Agawam, MA) synchronized with a high speed video camera (Photron, FASTCAM SA5, San Diego, CA). The camera lens was fitted with a 527nm band-pass filter to avoid reflections of the laser from the tissue. An area of 11.4 x 8.6mm in the physical space was captured for each image, corresponding to a pixel resolution of 922x698, respectively. Each image pair was taken at a time interval of 2.5µsec. Post processing of the PIV data was done using DAVIS 8.0® software (LaVision GmbH, Goettingen Germany) with a multi-pass decreasing window size (64x64 to 32x32) and adaptive interrogation window with 75% overlap.

The laser was focused and spread to produce a light sheet of 1 mm thickness, in the mid-coronal plane, halfway between the vocal process and the anterior commissure. It was placed such that the light sheet extended into the subglottis. The laser also reflected off the medial aspects of the folds allowing visualization of this tissue. The presence of the seeding particles allowed for clear differentiation between flow and the medial aspects of the fold. The mid-coronal plane was chosen, since tissue displacements and the magnitudes of the velocities are usually
highest in this section. Flow measurements were taken by placing the PIV camera above the vocal folds in an oblique angle that is sufficient to visualize the intraglottal flow. For the canines used in this experiment, the vertical height of the folds was approximately 2-3 mm. The camera was tilted at an angle of 40º, which was sufficient to observe the entire flow from the inferior to superior aspect of the glottis. The oblique viewing angle caused a limited depth to the field of view, which was solved by attaching a Scheimpflug optical adaptor to the lens of the camera.

A downstream microphone (½” free field microphone, Brüel & Kjær, 4950, Norcross, Georgia) was placed 5 cm to the side of the glottal exit in such a way that it did not interfere with laryngeal airflow. In addition a sound level meter (Larson Davis Inc, Model 831, Depew, New York) was placed opposite of the microphone to record the sound pressure level (SPL). An electroglottograph (EGG) was used and the electrodes were placed on both sides at the superior lateral aspect of the paraglottic space.

A high-speed video camera (Photron, Fastcam SA4, San Diego, CA) was placed approximately 1 meter above the glottal exit in order to visualize vocal fold vibration. The data from the microphone, pressure transducer, and EGG was digitized and recorded using a National Instruments (Austin, TX) PXI system. The timing and recording rates of all these systems were synchronized using a Timing and Synchronization module (National Instruments, Austin, TX). All the systems shared a common trigger to start the acquisition of the data.

For all larynges, the phonation threshold pressure (PTP) and the phonation instability pressure (PIP) was determine using the method of Zhang et al. (32). For each larynx, phonation trials were done at low, medium, and high subglottal pressures. The low and high pressures were set at approximately 2 centimeters (cm) of water (H2O) above PTP and 2 cm H2O below PIP, respectively. The middle subglottal pressure was set between the two. Each phonation trial lasted approximate one second allowing collection of about 50-60 vibrations and approximately 2,000 velocity fields.

RESULTS

An example of an intraglottal (including just above the glottal exit) velocity field is given in Figure 1. This is for high subglottal pressure at the mid to latter part of vocal fold closing (during vibration when the folds are coming together). The medial edges of the folds are shown in red. The left side of the figure represents the right fold, and vice versa. Flow separation was seen at high and mid subglottal pressures but not at low subglottal pressures. At low subglottal pressures, the folds were also seen to be straight during the entire closing phase (no divergence was determined).

Since the thickness of the PIV sheet is 1 mm, we can use the images to determine the flow rate (Q) that enters the inferior glottis and exits the superior glottis for this one mm section. In general, the flow rate is equal to the velocity multiplied by the area. In this case the area is the glottal width multiplied by the 1 mm thickness of the sheet. The velocity across the glottal width was not constant; this is especially true for the superior glottis. Therefore the velocity was integrated along the width; this value was multiplied by the 1 mm width of the section. Because of entrainment, the velocity at the superior medial aspect of the glottis is slightly negative (enters the glottis), whereas all of the airflow is positive at 0.5 mm above the folds. To account for entrainment effects, the flow rate at the glottal exit is determined when all velocities become positive. In Figure 2, the flow rates (Q) during closing are shown at the glottal entrance (most inferior edge of the folds) and the exit for the 1 mm thick mid-coronal glottal section for the larynx. It is seen that the flow rates do not differ much for low pressures. However, the flow rates at mid and high pressures were much greater at the superior aspect of the glottis than at the inferior aspect. Only flow rates for closing are shown in this figure, but the flow rate for opening at the glottal exit were approximately the inverse of the flow rates during closing at the inferior surface of the folds. We cannot get intraglottal velocity fields during opening using this method, so we can only determine the distance between the folds from the high speed imaging and the velocity at the glottal exit from the usual means during opening.

Figure 3 shows the distance between the folds at the mid-membranous location at the superior aspect of the folds. The distance during opening is determine by the high speed videography from above, this is accurate during closing since the shape of the glottis is convergent. During closing, high speed videography would give an accurate measurement of the inferior distance, but not the superior distance the glottis is divergent. Instead, the distance between the superior aspect of the folds during closing is determined from our cross sections. It is seen that there is no skewing of the area curve at the low pressures, but that there is skewing at the mid to higher pressures.
FIGURE 1. Coronal intraglottal velocity field and medial aspect of the folds at the mid-membranous location of the folds. The medial aspect of the red represents the medial aspect of the fold. The bottom arrows represent the inferior medial aspect of the fold and the top arrows represent the superior medial aspect of the folds.

FIGURE 2. Flow rate for the 1 mm thick cross section at the mid-coronal location for the inferior and superior edge of the folds at the three different subglottal pressures. The x axis refers to the phase of vibration, where 0 and 360 degrees marks the beginning of opening (when the superior edge of the folds are seen to come apart by high speed videography). These curves are only measured for closing (see text for discussion), where closing is defined when the medial aspect of the folds (again by high speed videography) are seen to come together’ during closing, this corresponds to the medial aspects of the inferior folds.
**DISCUSSION**

This work shows that for this larynx, the flow rate just above the superior fold is greater than it is at the inferior fold. This is thought to be due to entrainment. In other larynges (to be reported in a future paper), entrainment is always seen at mid to higher subglottal pressures, so this phenomenon should occur in general. Skewing of the flow rate curve does occur at mid to high subglottal pressures, where the flow rate at both inferior and superior edges decreases much more rapidly than it increases. In this one larynx, the MFDR is higher at the superior aspect than the inferior aspect, although they are close enough that this phenomenon needs to be studied in more larynges.

It is interesting to note the skewing of the distance curve (Figure 3) at mid to high subglottal pressures but not at low. We hypothesize that this is due to the effect of the intraglottal vortex only seen at mid to high subglottal pressures. This vortex will produce a negative pressure, which can cause the superior aspect of the folds to come together rapidly, which could also cause the inferior folds to come together rapidly. This hypothesis would explain why there is skewing of the flow rates at both the inferior and superior edge since entrainment would not explain this. However, this hypothesis is precisely that much more work is needed to test its validity. These findings are interesting and are slightly different than would be predicted by current theoretical models. Nonetheless, much further work is needed to make sure these findings are statistically significant and to explain them; doing so will improve our understanding of the mechanisms of vocal fold vibration and of the relationship between the flow rate curve and acoustics.

Khosla et al (2007), Verneuil et al (2000) and Alipour and Scherer (2000) have all shown that velocity fields are similar at the anterior, middle, and posterior vocal fold locations. Verneuil et al also showed that the area curves are similar. It is very likely that validity of the assumption that the area and velocity curves will be similar in shape depends on the type of anterior-posterior vibration pattern. If there is no or minimal anterior-posterior mucosal wave, as was the case with this larynx, then the assumption is reasonable. However, if there is a significant anterior-posterior mucosal wave, such as is seen in the zipper-type closure pattern, then it is not reasonable. Since there is no zipper pattern seen in the case reported in our paper, it is likely that the cross-sectional flow rate is representative of the total flow rate.

**Figure 3.** The distance between the superior aspect of the folds as a function of the time in the vibration cycle. Theta is defined such that the beginning and ending of vocal fold vibration is 0 and 360 degrees respectively, which is determined by high speed videography. The distance is measured from high speed videography during opening and the cross-sections obtained from PIV for closing (see text for details).
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REFERENCES


