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# Flow and acoustic measurements in the canine larynx model

**L Oren[1,2]*, C Farbos De Luzan[1], S Khosla[1] and E Gutmark[2]**

[1]University of Cincinnati (UC) College of Medicine, Department of Otolaryngology, Cincinnati, Ohio, USA

[2]University of Cincinnati, Department of Aerospace Engineering and Engineering Mechanics, Cincinnati, Ohio, USA

*liran.oren@uc.edu

## Abstract

## 1 Introduction

Normal speech is produced by a combination of sound and airflow that begins when air from the lungs travels through the vocal folds and articulators (e.g., tongue, lips). In the classic source-filter model of speech production (Fant, 1960), sound is initiated with phonation, which occurs when vibration of the vocal folds causes modulation of the airflow. In this case, "flow" specifically refers to the flow rate (Q) produced at the glottal exit during the phonation cycle. Flow modulation refers to the fact that Q is changing as the vocal folds open and close ($dQ/dt$).

Although $dQ/dt$ is constantly changing during the opening and closing phases of the vocal folds vibration, the greatest rate of change happens during the latter part of closing, when Q rapidly decreases. This rapid deceleration is quantified by the maximum flow declination rate (MFDR). MFDR has been found to correlate with vocal efficiency (Stevens, 1999). Vocal efficiency is a measure for how aerodynamic power from the lung is transferred into acoustic energy radiated from the vibrating folds. In short term, higher vocal efficiency means that the vocal folds vibrate with fewer "losses" of power in the larynx, and thus can vibrate longer (or louder) without risk of vocal trauma.

Direct measurements of the glottal flow in humans are challenging because of the physical constraints (i.e., *in situ* location) and the fast timing of the glottal events (vocal folds typically vibrate at 100Hz-250Hz). In recent years, particle image velocimetry (PIV) have become the method of choice for measuring Q. The technique can quantify (non-intrusively) the spatial and temporal information of the flow. The current study is the first to measure Q at the glottal exist during vocal folds vibration in a canine larynx, the model most often used to study phonation in a tissue model of the larynx. The results can then extend to model voice mechanisms.

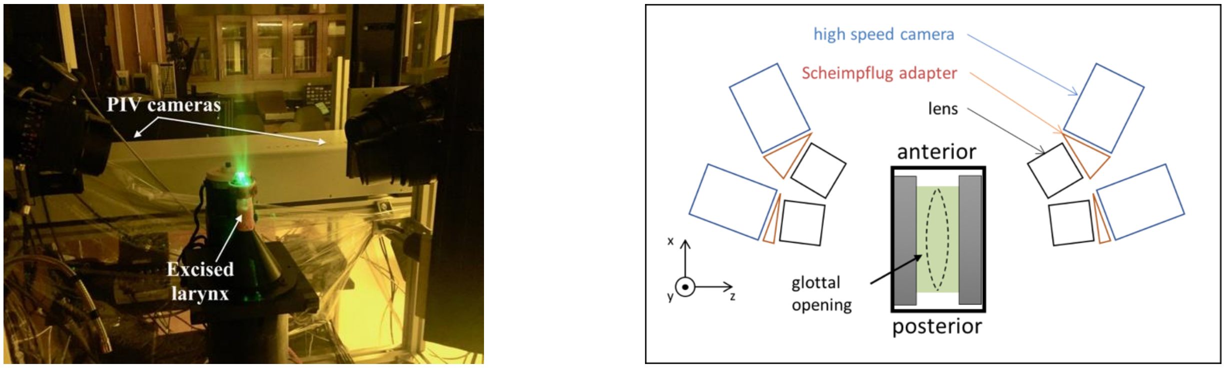
## 2 Methods

In an excised canine larynx model, flow measurements were made using time-resolved tomographic particle image velocimetry (tomo-PIV). Excised larynges were harvested from shared research canines immediately after the animals were euthanized. All structures above the vocal folds were removed to obtain an unobscured view of the folds. The larynx was suspended using a pronged apparatus that also provided adduction of the vocal folds. The trachea was placed over an aerodynamic nozzle that conditioned the airflow before it entered the glottis.

The pressure inside the aerodynamic nozzle was measured with a pressure transducer (FPG, 0-50cmH2O, Honeywell) and was used to calculate the subglottal pressure (i.e., lung pressure). Upstream of the larynx, the mean flow rate, Q, was measured using a coriolis flow meter (CMF025, MicroMotion Inc).

For tomo-PIV measurements, the flow existing the glottis was illuminated from above the larynx. High-speed video cameras were arranged circumferentially around the anterior at (about) the level of the vocal folds (Figure 1). Time-resolved PIV measurements were taken at 3kHz with a spatial resolution of 38.8 pixels/mm.

The tomo-PIV measurements were taken simultaneously with acoustic measurements during phonations at different subglottal pressure (i.e., lung pressure) levels. Acoustic measurements were made using a ¼" multi-field microphone (model 4961, Bruel & Kjær) that was placed 15cm laterally and superiorly to the glottis. Signal acquisition of the microphone and pressure transducer was made at 20kHz and was synchronized with the PIV measurements using a data acquisition system (PXIe-6356 and PXIe-6672, National Instruments).



**A** **B**

Figure 1. Tomo-PIV measurements in the canine larynx. a) Laser is projected from above the larynx. PIV cameras are positioned circumferentially and anteriorly to the larynx. b) Top-view schematics illustrating the setup for the tomo-PIV measurements.

## 3 Results

PIV velocity measurements captured the unique characteristics of the glottal flow (Figure 2). Velocity measured between the vibrating folds showed formation of vortices near the superior aspect of the folds during the latter part of the closing phase (Fig. 2a). These intraglottal vortices, defined as flow separation vortices (FSV), produce negative pressures between the superior half of the folds (Oren et. al. 2014). The strength of these vortices was proportional to the subglottal pressure and the acoustic intensity (SPL). Volume flow velocity was measured above the glottal exit (Fig. 2b).

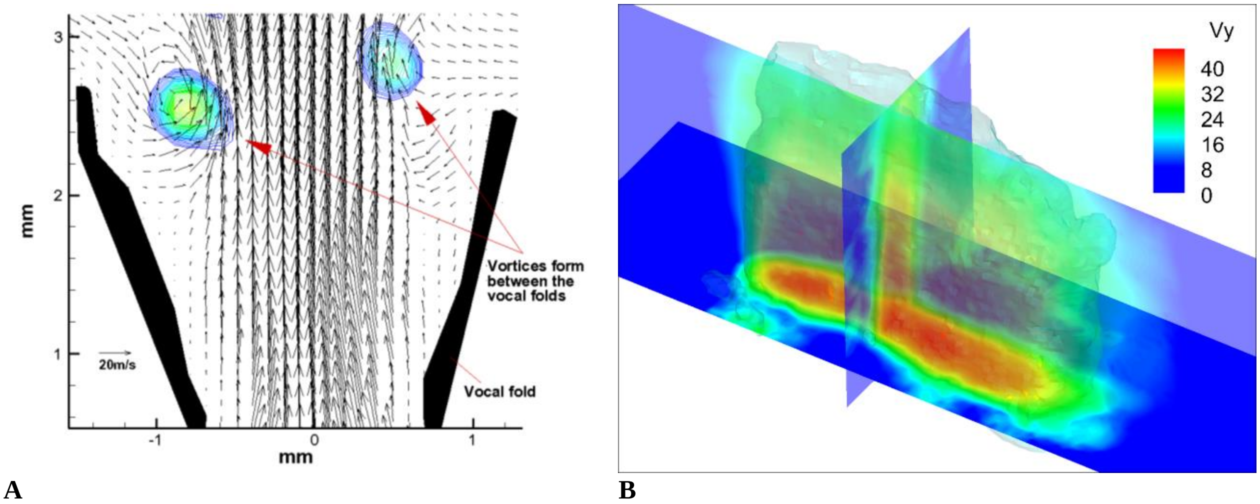


Figure 2. Flow velocity measurements using PIV. a) Between the vibrating folds during the closing phase. Flow separation vortices form near the superior aspect of the vocal folds. b) Volume flow measurements above the glottis during closing.

For each subglottal case, the waveform of Q was extracted at the glottal exist (Figure 3a). The computed waveform for Q from the PIV velocity measurements was validated by comparing its mean with the upstream measurement of the flow rate (Figure 3b). The validation process showed that the computed flow rate from PIV can be matched of its upstream measurement (<1% difference) within 3-4 mm above the glottal exit.

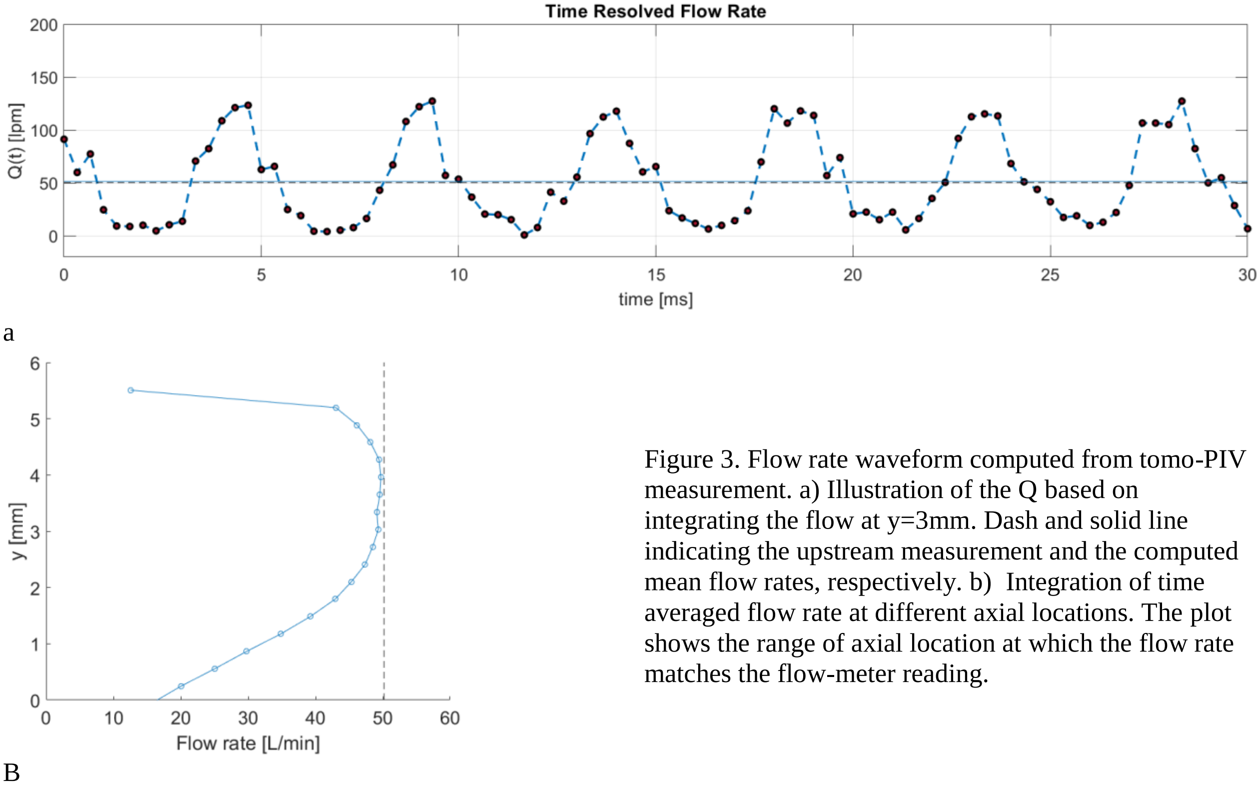
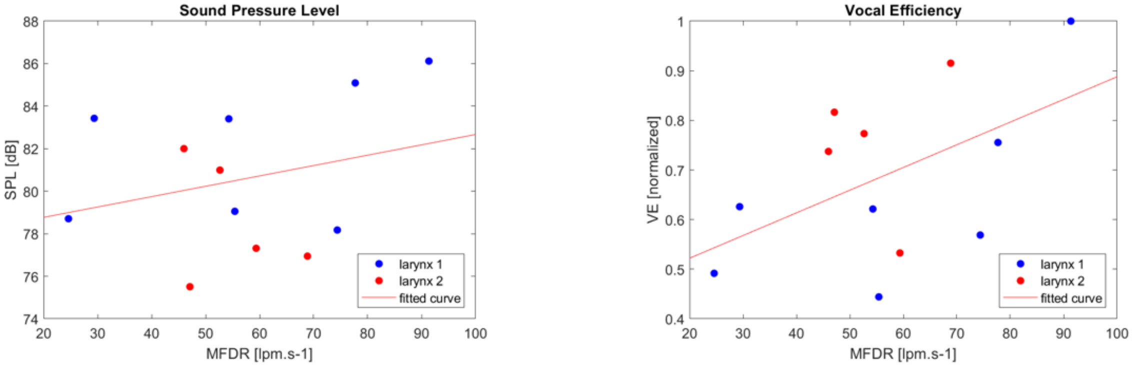


Figure 3. Flow rate waveform computed from tomo-PIV measurement. a) Illustration of the Q based on integrating the flow at y=3mm. Dash and solid line indicating the upstream measurement and the computed mean flow rates, respectively. b) Integration of time averaged flow rate at different axial locations. The plot shows the range of axial location at which the flow rate matches the flow-meter reading.

MFDR was calculated from the glottal waveform for each subglottal pressure. Acoustic measurements were used to calculate the vocal efficiency for each case. The results showed that increasing the subglottal pressure corresponded to an increase in MFDR and subsequently increases in acoustic energy and vocal efficiency (Figure 4).



(a) (b)

Figure 4. Increase in MFDR corresponds to increases in a) acoustic intensity and b) vocal efficiency.

## 4 Discussion

As the first study (to the best of our knowledge) to measure flow rate (Q) at the glottal exist during vocal fold vibration in a canine larynx, the findings are significant because they validate existing theories about voice mechanism and provide experimental data for validation of future experimental data. PIV velocity measurements captured the unique characteristics of the glottal flow model, specifically the existing of FSV near the superior aspect of the vocal folds during the closing phase of vibration.

Acoustic intensity can be increased by increasing the subglottal pressure (which also increases MFDR). For example, increasing lung pressure results in a louder voice but can also cause trauma related to vocal tissue strain (e.g., shouting too much and losing one's voice). Therefore, there is a clinical need to increase MFDR (or acoustic intensity) in a healthy manner. Vortices formed near the superior aspect of the folds generate negative pressure. This effect in turn can act as an additional "suction" force that can add to the rapid closure of the folds (thus increasing MFDR). However, methods to increase the strength of these vortices, without increasing the subglottal pressure, are still being investigated.

## Acknowledgements

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