Impact of vertical stiffness gradient on maximum divergence angle

Sid Khosla, MD, Alexandra Maddox, Charles Farbos de Luzan, PhD, Liran Oren, PhD, Ephraim Gutmark, PhD
Department of Otolaryngology- Head and Neck Surgery, University of Cincinnati

INTRODUCTION

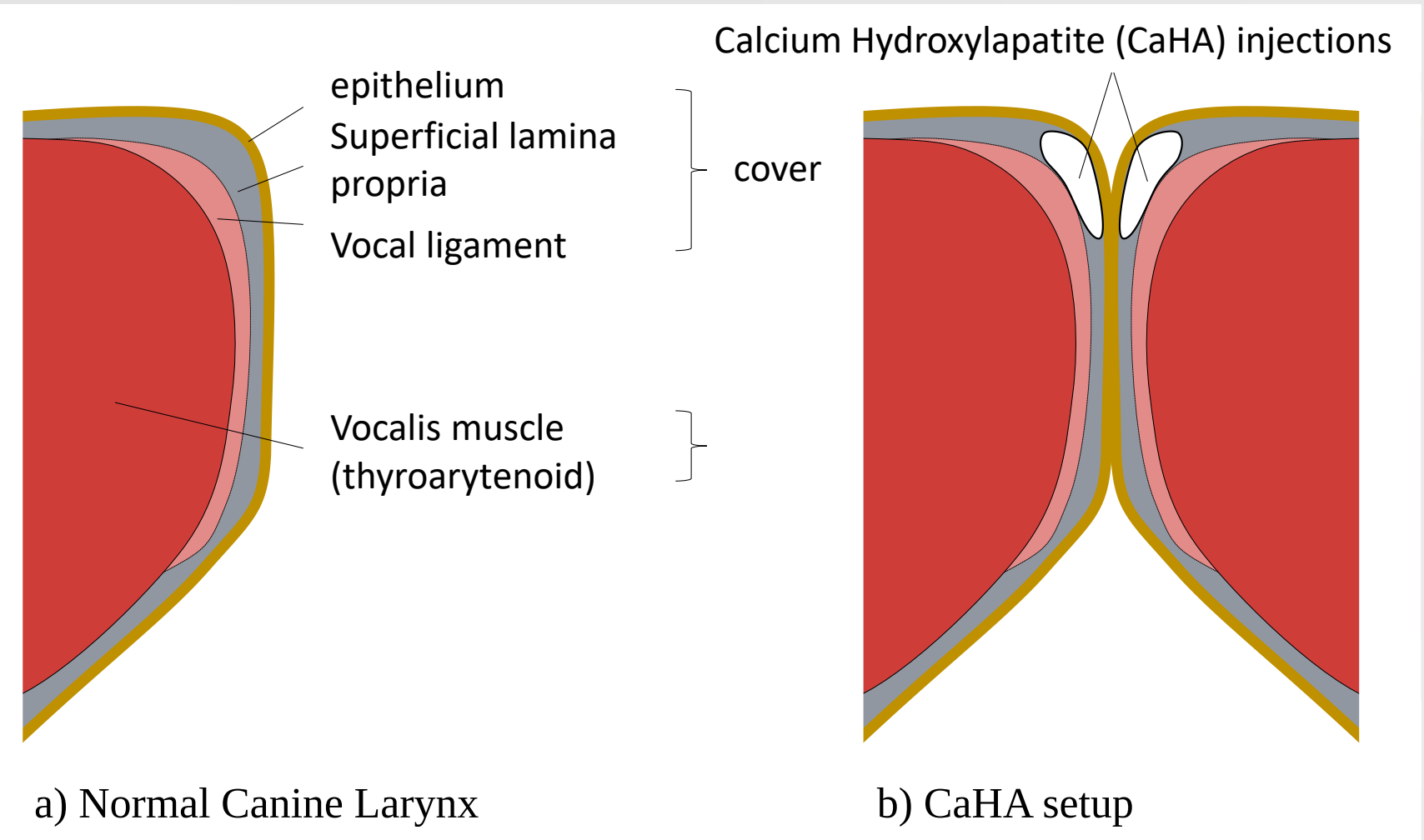
During vocal fold vibration, the coronal shape of the glottis is convergent during opening and divergent during closing. This movement results in a phase delay between the inferior and superior edges of the glottis, referred to as the vertical phase difference. The vertical phase difference is critical to phonation, it results in higher pressures when the glottis is convergent and lower pressures when the glottis is divergent[1,2,3,4], making it a driving force of phonation[5,6]. The vertical phase delay is also associated with large divergence angles during closing, which are associated with increased acoustic intensity, vocal efficiency, and higher harmonics.

It is hypothesized that the cause of the vertical phase difference is the vertical stiffness gradient of the glottis, in which the superior aspect of the fold is not as stiff as the inferior aspect of the fold[7,8]. Thus for similar applied pressure, the superior edge would displace farther than the inferior edge, resulting in a large divergence angle during closing, which would result in a large phase delay between the inferior and superior edges. In computational models, Geng found that an increase in the vertical stiffness gradient resulted in larger divergence angles during closing, and thus a larger phase delay, and Yang et al. showed that there must be a vertical stiffness gradient to match experimental results. The effect of the vertical stiffness gradient has not, however, been studied experimentally.

METHODS

Measurements were taken in four excised canine larynges. Measurements of intraglottal flow, medial wall geometry, and tissue elasticity in the mid-membranous coronal plane were taken before (baseline) and after calcium hydroxylapatite (CaHA) was injected into the superior edge. CaHa was used to stiffen the superior edge of the vocal fold, and was injected only at the superior medial edge (.1-.2ml per fold)(Figure 1).

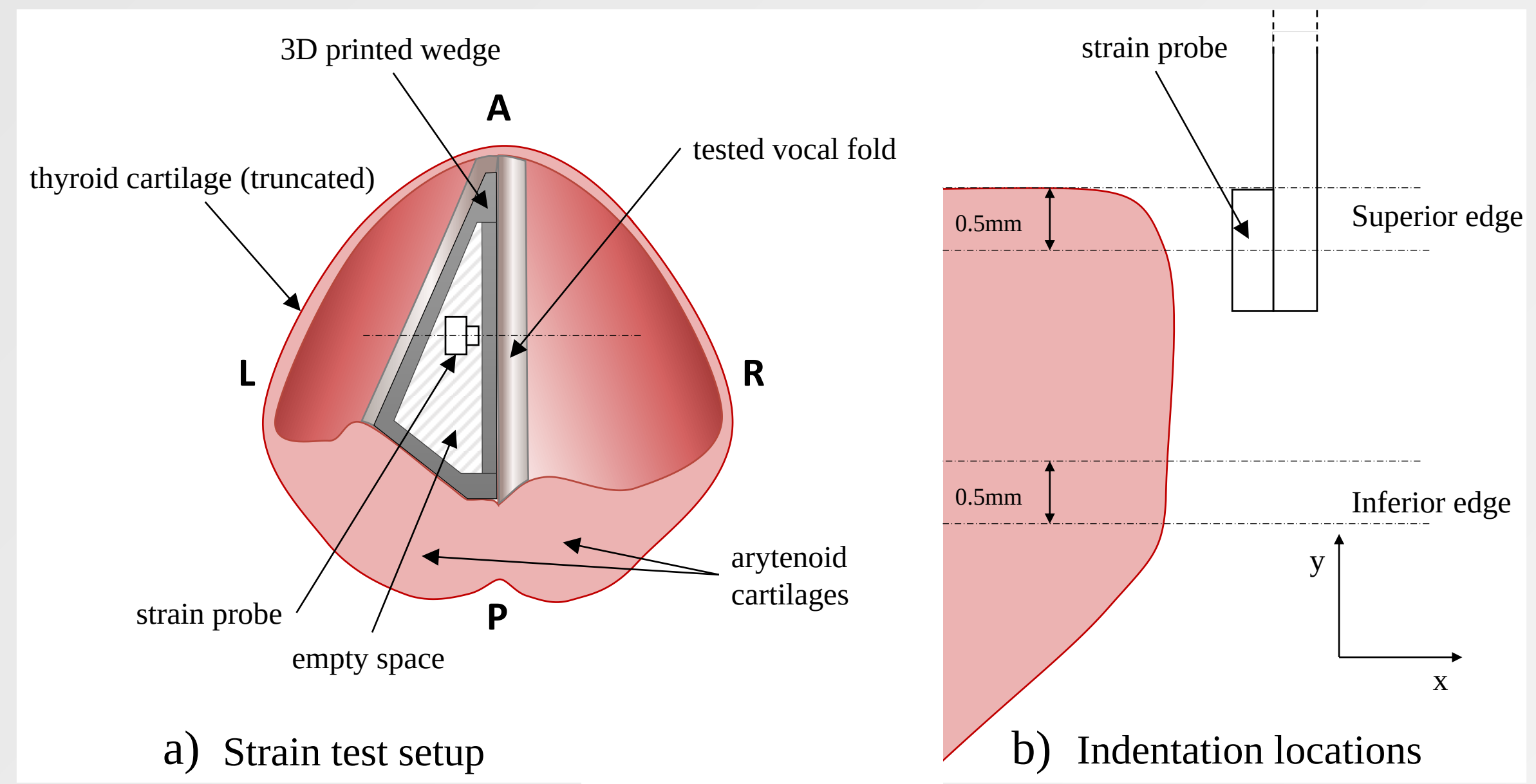
Figure 1:



a) Normal Canine Larynx
b) CaHA setup

Tissue elasticity was measured using the indentation technique in which force was measured using a custom built 1mm probe that traversed by .2mm increments into the tissue. Indentation testing was performed at the inferior and superior edges of the vocal fold both before and after the CaHA injections (Figure 2). Intraglottal flow and medial wall geometry were measured using particle image velocimetry (PIV). PIV is a flow measurement technique that uses high speed cameras that capture a laser illuminated flow field to determine the velocity of micro particles in the flow.

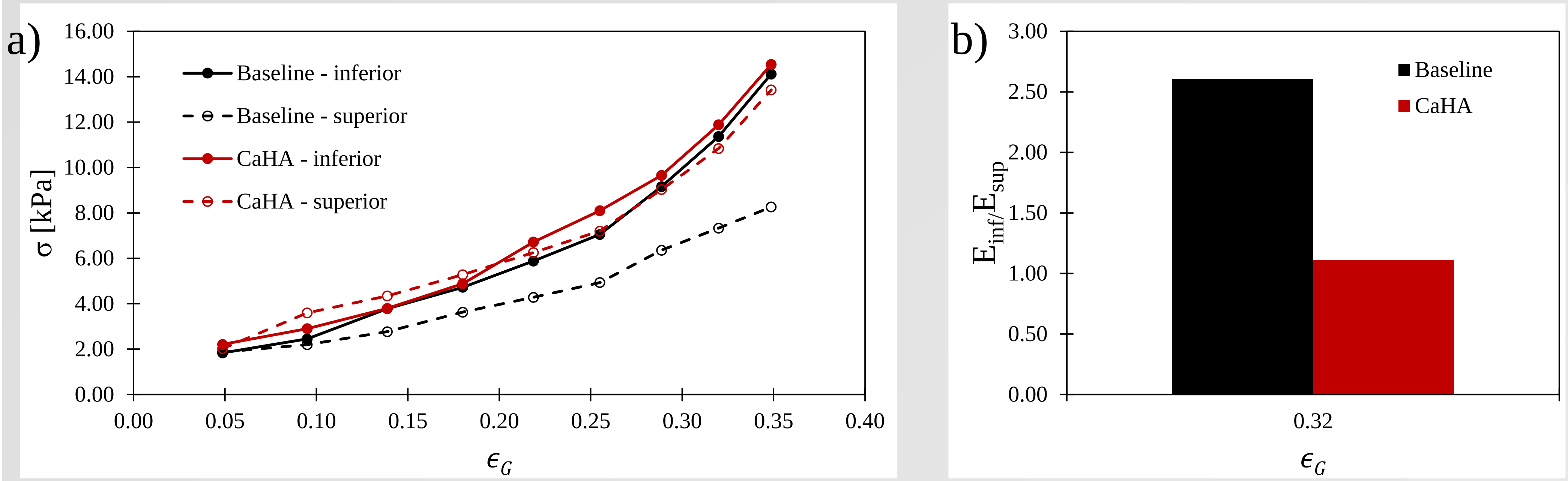
Figure 2:



a) Strain test setup
b) Indentation locations

RESULTS

Figure 3:



The averaged results of the stiffness characterization by indentation testing on the four larynges are shown in figure 3. It shows that injecting CaHA in the superior aspect of the folds reduces the vertical stiffness gradient by stiffening the superior aspect of the folds. The stress-strain curves of the inferior edge (solid lines) do not change much between pre- and post-injection, as expected. The red dash curve, however, is shifted upward from the black dashed curve. This means it takes more stress to achieve the maximum strain after injection of CaHA at the superior edge (Fig. 3a).

Stiffness gradients are much-reduced post-CaHA injection, as the ratio of Young modulus shows (Fig. 3b). The ratio of averaged Young's modulus is larger than one in a normal larynx (the inferior aspect stiffer than the superior aspect), and close to one post-CaHA injection at the beginning of unloading. It illustrates the stiffening of the superior edge by CaHA injection.

Figure 4:

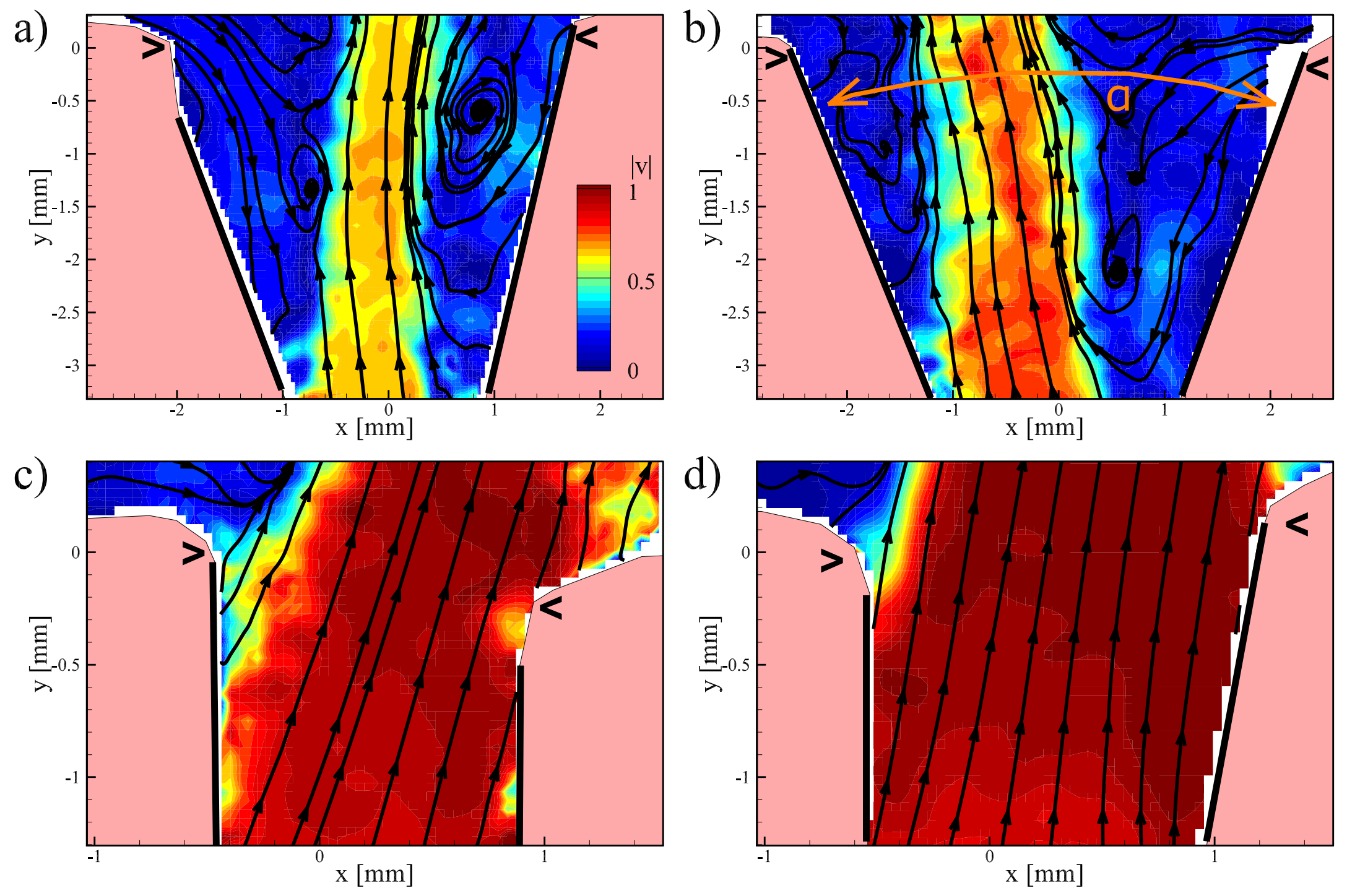
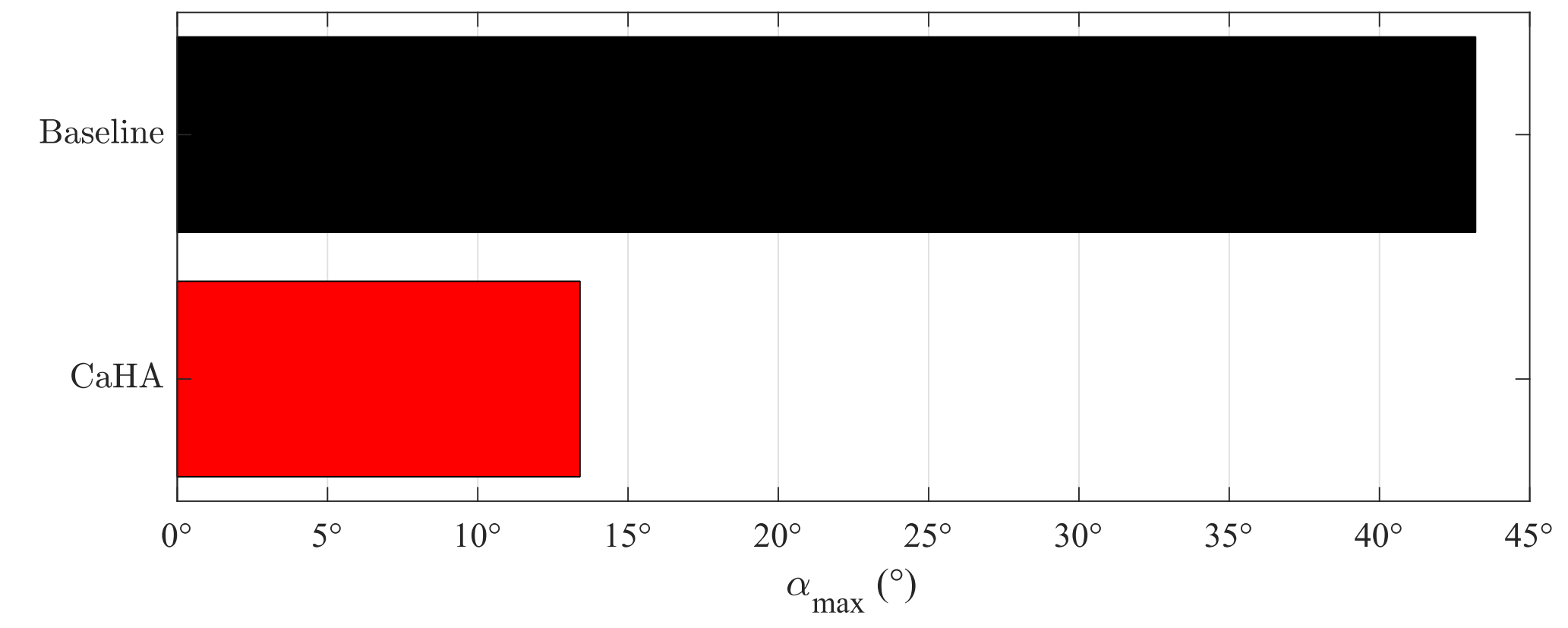


Figure 5:



The maximum divergence angle was much reduced post-injection. This was shown using instantaneous velocity fields that delineate the intraglottal geometry at the phase when maximum divergence angle occurred during closing (Fig. 4). Before CaHA injection the divergent shape of the glottis during closing causes the glottal jet to separate from the medial wall and intraglottal flow separation vortices to form near the superior aspect (Fig. 4a,b). After CaHA injection (Fig. 4c,d) the divergent angle is eliminated at low subglottal pressures and reduced at high subglottal pressures; in both cases, the flow does not separate from the wall and there are no intraglottal vortices.

CaHA injection and stiffening the superior edge subsequently reduced the maximum divergence angle for all cases (Fig. 5). The reported divergence angles were measured between the left fold and the right fold, so they represent the total glottal opening angle (see Fig. 4b). All baseline larynges exhibited a divergent shape during closing that ranged from 38° to 54°, with an average of 43°. After injecting CaHA in L1 and L2, the divergence angle never exceeded 10°. L3 was injected with less CaHA and had an average divergence of 23°. This suggest a direct correlation between the stiffness gradient and the resulting intraglottal angle during closing.

Figure 6:

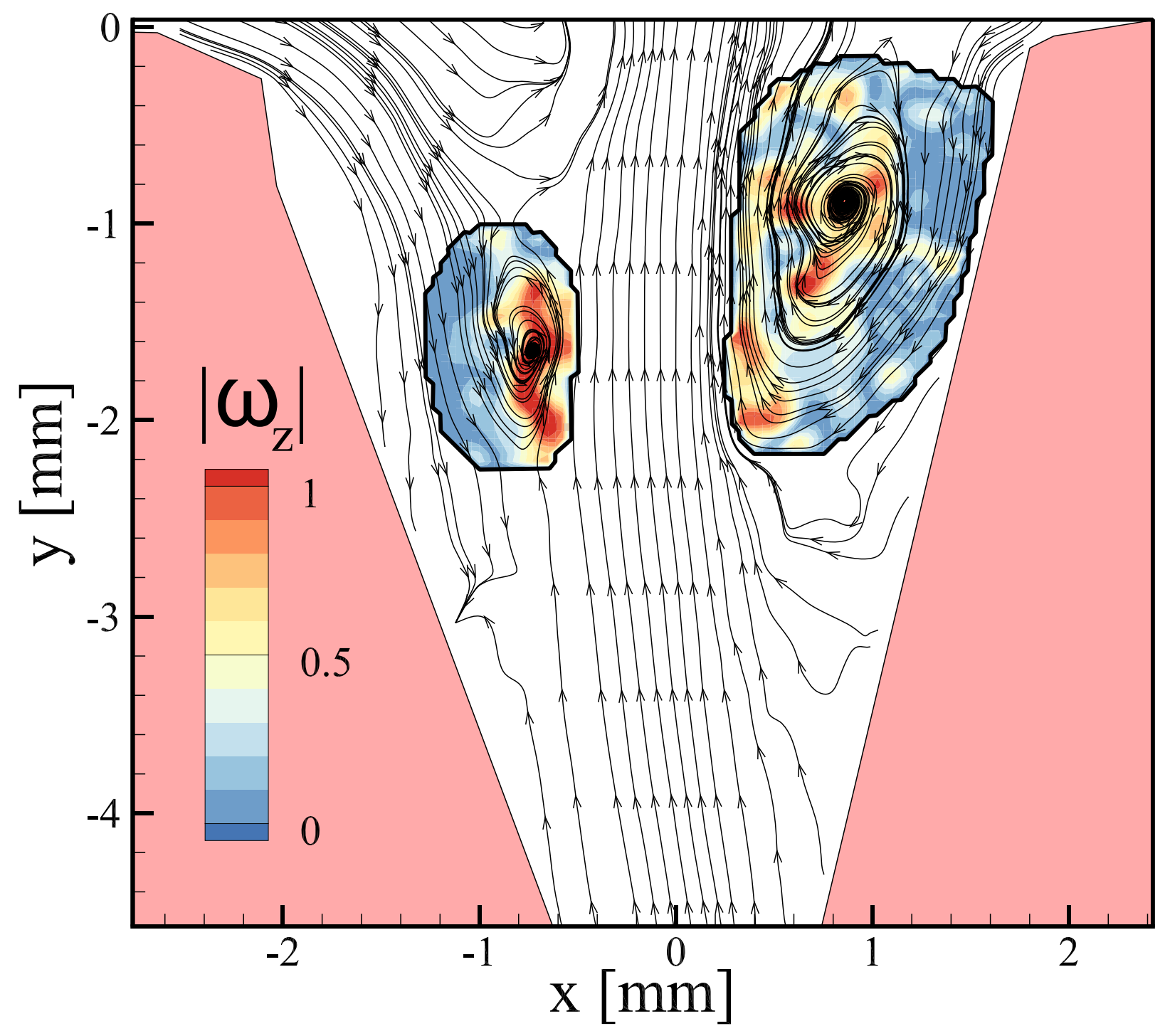
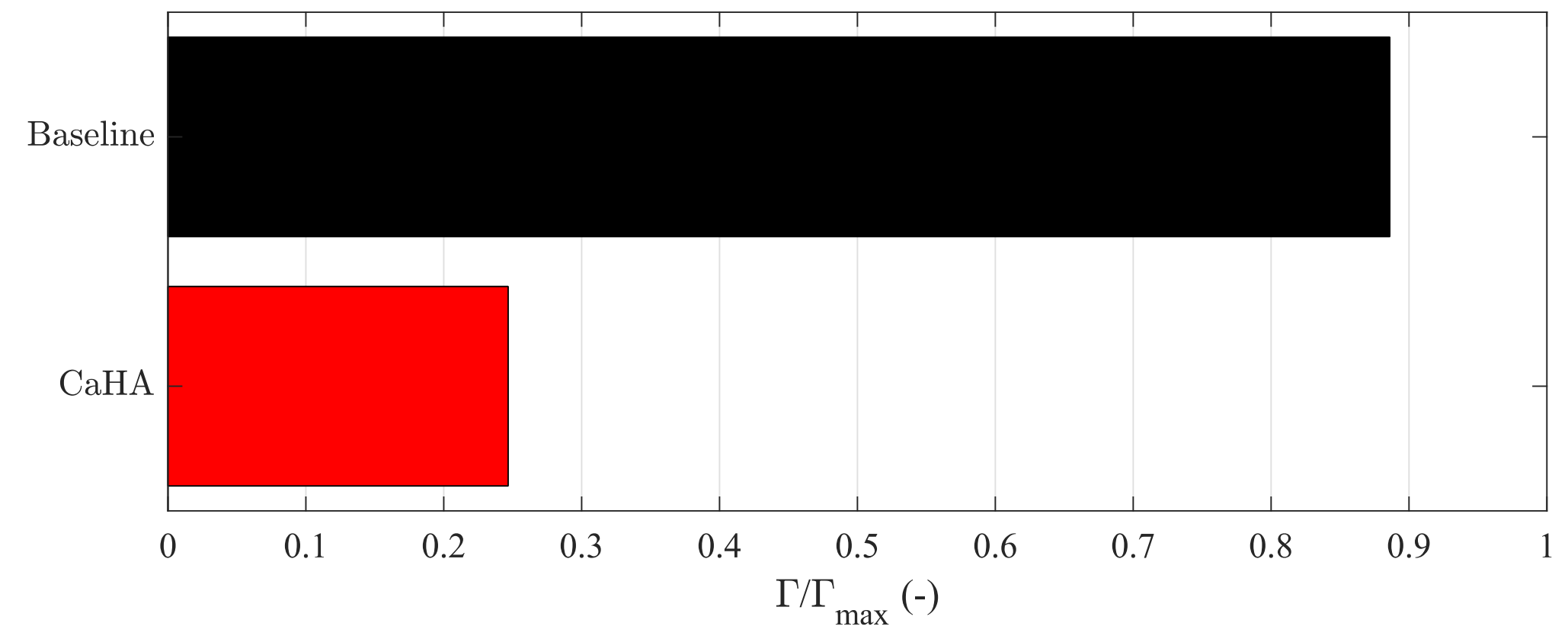


Figure 7:



The strength of the intraglottal vortices was quantified using circulation, to quantify the amount of rotation between the separated glottal jet and the folds. Contours of normal vorticity ω_z are plotted inside the integration area, which is used for the calculation of the vortex circulation (Fig. 6). Reduced divergence angles resulted in reduced intraglottal vortical strength (Fig. 7). Prior to injection, the baseline cases had large divergence angles during closing, and flow separation vortices formed near the superior edge, resulting in high vortical strength. Following the CaHA injections, little to no flow separation occurred thus, there was very low circulation strength.

Flow separation vortices form when outside flow enters and exits the vortex but the rotational motion remains relatively stationary. FSV produce negative gauge pressures that reduce the fluid resistance to the elastic forces that close the glottis. Our hypothesis is that a divergent glottis will feature a higher closing speed than the relatively straight glottis, which will result in greater acoustic power (as measured by an increase in SPL). For example, our computational colleagues (Xudong Zheng and Qian Xue, personal communication) have shown, using a computational model, that increasing these intraglottal negative gauge pressures can increase closing speed by up to 30%. Thus, with the same subglottal pressure, the more divergent glottis will produce greater SPL. This increases vocal efficiency (acoustic power/aerodynamic power) which clinically translates to easier phonation and decreased vocal fatigue.

CONCLUSIONS

Decreasing the vertical stiffness gradient decreased the maximum divergence angle, which reduced or eliminated the flow separation vortices. The elastic properties of the vocal folds were locally modified using Calcium Hydroxylapatite (CaHA) to reduce the VSG by increasing the stiffness near the superior edge. This yielded a reduced divergence angle during the closing of the phonating glottis. The flow separation vortices, when generated, displayed less circulation in the case of the reduced divergence than in the healthy baseline cases. This supports the hypothesis that reducing the vertical stiffness gradient is associated with a decrease in the maximum divergence angle and a decrease or elimination of the flow separation vortices. The decreased vertical phase difference (which corresponds to a reduced maximum divergence angle) has been shown clinically to be correlated with a decrease in vocal efficiency.

University of Cincinnati

REFERENCES:

1. Thomson SL, Mongeau L, Frankel SH. Aerodynamic transfer of energy to the vocal folds. *J Acoust Soc Am*. Published online 2005. doi:10.1121/1.2000787 2. Xue Q, Zheng X, Mittal R, Bielamowicz S. Subject-specific computational modeling of human phonation. *J Acoust Soc Am*. 2014;135(3):1445-1456. 3. Alipour F, Scherer RC. Dynamic glottal-pressures in an excised hemilarynx model. *J Voice*. Published online 2000. doi:10.1016/S0892-1997(00)80002-8 4. Oren L, Gutmark E, Khosla S. Intraglottal velocity and pressure measurements in a hemilarynx model. *J Acoust Soc Am*. Published online 2015. doi:10.1121/1.4906833 5. Titze IR. The physics of small-amplitude oscillation of the vocal folds. *J Acoust Soc Am*. 1988;83(4):1536-1552. doi:10.1121/1.395910 6. Zhang Z, Neubauer J, Berry DA. Physical mechanisms of phonation onset: A linear stability analysis of an aeroelastic continuum model of phonation. *J Acoust Soc Am*. Published online 2007. doi:10.1121/1.2773949 7. Chhetri DK, Zhang Z, Neubauer J. Measurement of Young's modulus of vocal folds by indentation. *J Voice*. 2011;25(1):1-7. doi:10.1016/j.jvoice.2009.09.005 8.Oren L, Dembinski D, Gutmark E, Khosla S. Characterization of the vocal fold vertical stiffness in a canine model. *J Voice*. Published online 2014. doi:10.1016/j.jvoice.2013.11.001 9. Geng B, Xue Q, Zheng X. The effect of vocal fold vertical stiffness variation on voice production. *J Acoust Soc Am*. 2016;140(4):2856-2866. doi:10.1121/1.4964508 10. Chhetri DK, Zhang Z, Neubauer J. Measurement of Young's modulus of vocal folds by indentation. *J Voice*. 2011;25(1):1-7. doi:10.1016/j.jvoice.2009.09.005