The Effects of the False Vocal Folds on Translaryngeal Airflow Resistance

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Abstract

The human larynx is a tube with two orifices, with the false vocal folds (FVF) just above the true vocal folds. The gap between the two false vocal folds can vary during speech and may affect the aerodynamics and aeroacoustics of phonation, the extent of which is not yet known.

The present research was conducted to understand the effects of the false vocal fold gap on translaryngeal airflow resistance (translaryngeal pressure divided by volume flow). A scaled-up static Plexiglas model of an adult larynx was used. Prior to simulating the laryngeal geometry, a study was conducted to determine the shape and size of the false vocal fold region using human laminagrams obtained during phonation. Selected features from the results of the study were used to build models of the false vocal folds. These were placed in the Plexiglas model of the larynx to study the effects of the false vocal fold gap on translaryngeal airflow resistance.

The FVF gap was parametrically varied for each of five glottal diameters and five glottal angles. Seven different pressure drops were used for each laryngeal geometry. Results showed that the translaryngeal airflow resistance decreased by about 10-25% for all glottal diameters for specific FVF gap sizes. Minimum airflow resistance for any glottal condition was observed when the false vocal fold gap was about twice the minimal glottal diameter. The airflow resistance was lowered more for converging and uniform cases than for divergent ones. For glottal diameters of 0.04 and 0.08 cm, the airflow resistance was lowered for a wider range of FVF gaps than for glottal diameters of 0.16 and 0.32 cm. A best fit for the entire data is also provided.

This decrease in translaryngeal airflow resistance may be indicative of efficient voice production, and may suggest target laryngeal anatomy for optimal surgical and rehabilitative vocal intervention.

1. Introduction

The true vocal folds are considered to be the main vibratory source of sound. Research exploring the role of the supraglottal region in voice production is comparatively minimal. This research project explored the effect of one of the supraglottal structures, the false vocal folds, on laryngeal flow resistance.

The false vocal folds have been shown to take different positions with different intensities and vowels (van den Berg, 1955; Wilson, 1972, 1976), frequency (Wilson, 1972, 1976), and vocal register (Allen and Hollien, 1973). The false vocal folds reportedly adduct, particularly in anterior parts, during certain types of throat singing (Kobayashi and Tohkura, 1989; Fuks et al., 1998; Lindestad et al., 2001). Such types of throat singing result in a perceptually strained and effortful voice but curiously are rarely associated with any major vocal pathology. In addition, the false vocal folds also adduct towards the midline in the presence of vocal pathologies and may vibrate (von Doersten et al., 1992; Nasri et al., 1996) or not (Pinho et al., 1999).

Since the false vocal folds are located superior to the true vocal folds at a close distance, it is important to hypothesize that the presence and adduction of these folds might modify the laryngeal airflow in some manner. The true vocal folds and the false vocal folds in the human larynx form two orifices placed closely together with a cavity (ventricle) in between. Research in fluids engineering have shown different aerodynamic patterns with double or multiple orifices compared to a single orifice (Seeley and Young, 1976; Talukder et al., 1977; Dreumel and Kuiken, 1989). In general, an increase in the overall pressure drop with an increase in the number of orifices in a tube is suggested. It is possible that similar effects are observed in the larynx. The geometry of the larynx, though similar, is not the same as those used in the fluid mechanics studies, however. The differences in geometry might significantly change the aerodynamic and aeroacoustic properties, and thus the overall results for the system.

Recent studies with computational models (Zhang et al., 2002; Rosa et al., 2003) as well as physical models (Kucinschi et al., in review) of the larynx show that the false vocal folds may play a more positive role in both the physiology and acoustics of voice production. These studies, however, are limited in the phonatory geometries considered.

In the present study, we explore the aerodynamic effects of the FVF gap on translaryngeal airflow resistance for glottal shapes, angles, and widths encountered during complete cycles of the true vocal folds.

2. Method

The effect of the false vocal folds on the translaryngeal airflow resistance was studied using a Plexiglas model of the larynx, M5. Model M5 is a 7.5 times scaled-up model of an adult male larynx. Five glottal angles (40 deg divergent, 20 deg divergent, uniform, 20 deg convergent, and 40 deg convergent) and five widths (0.02, 0.04, 0.18, 0.16, and 0.32 cm) were used to represent important geometries often appearing within phonatory vibratory cycles. The false vocal fold gap was parametrized with 5-7 different values. Seven translaryngeal pressure drops ranging from 1-25 cm H_2O (1, 3, 5, 10, 15, 20, 25 cm H_2O) were used for each condition.

True vocal folds representing a particular symmetric glottal angle were placed in the model and the minimal glottal diameter was created with shims. An intended translaryngeal pressure was established across the true vocal folds by adjusting the flow through the model. Flow voltage was measured for each condition using a multimeter. Flow Resistance was calculated by dividing the translaryngeal pressure drop by the prevailing flow. The flow resistance was initially estimated only for the true vocal folds, i.e., without the presence of the false vocal folds. This served as a baseline for the flow resistance that was measured in the presence of the false vocal folds.

The false vocal folds with the widest gap between them were later placed in the model, keeping the same glottal geometry, at an downstream distance of 0.60 cm from the true vocal folds. The specific value of 0.60 cm was adopted from a previous study on false vocal fold geometry (Agarwal et al., 2003) and represents the average height of the false vocal folds from the true vocal folds for a normal adult male phonating the vowel /a/ in modal register. The false vocal folds were parametrically brought closer together and the process repeated.

Pressure distributions in the glottis were obtained for a few experimental cases to see if the intraglottal pressure distribution was altered in anyway due to the presence of the false vocal folds.

3. Results

The non-dimensionalized resistance for a 40° divergent glottal angle versus false vocal fold gap is shown in **Figure 1**, where the nondimensionalized resistance is defined as the flow resistance with the false folds present divided by the flow resistance without the false folds present. **Figure 2** shows the same non-dimensionalized resistance against non-dimensionalized false vocal fold gap (G_{FVF}/Dg), where Dg is the minimal glottal diameter.

From Figure 2 it is observed that for all cases, the non-dimensionalized resistance can be expected to fall in one of the three categories depending on the non-dimensional gap between the false vocal folds. (1) The non-dimensionalized resistance in the presence of the false vocal folds remained the same as in their absence when the false vocal fold gap was approximately eight times or more than the glottal diameter (Dg); (2) for the lower range of the normalized false vocal fold gap, i.e., below a value of about 1.0 for G_{FVF}/Dg, the non-dimensionalized resistance increased dramatically; (3) for the intermediate range of the false vocal fold gap, the non-dimensionalized airflow resistance *decreased* for all cases, exhibiting a minimum before rising back again, except when the glottal diameter was 0.02 cm for all divergent and uniform cases. This intermediate range of the false vocal fold gap of decreased airflow resistance varied with glottal diameter.

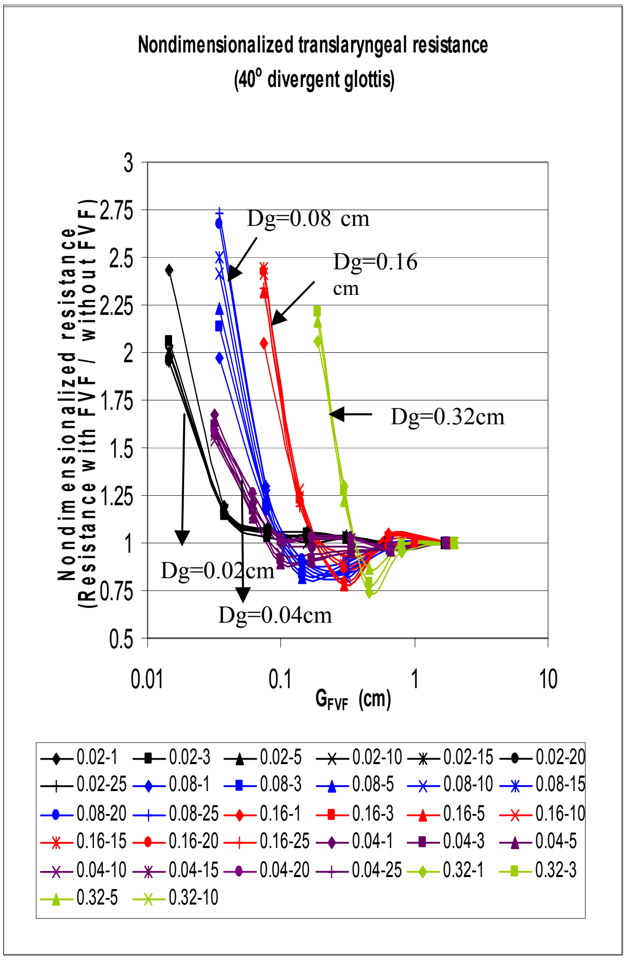

Figure 1. Non-dimensionalized translaryngeal airflow resistance for a 40° divergent glottis with various false vocal fold gaps. Each set of colored lines represent a glottal diameter. Various lines in each set represent different pressure drops used for that condition.

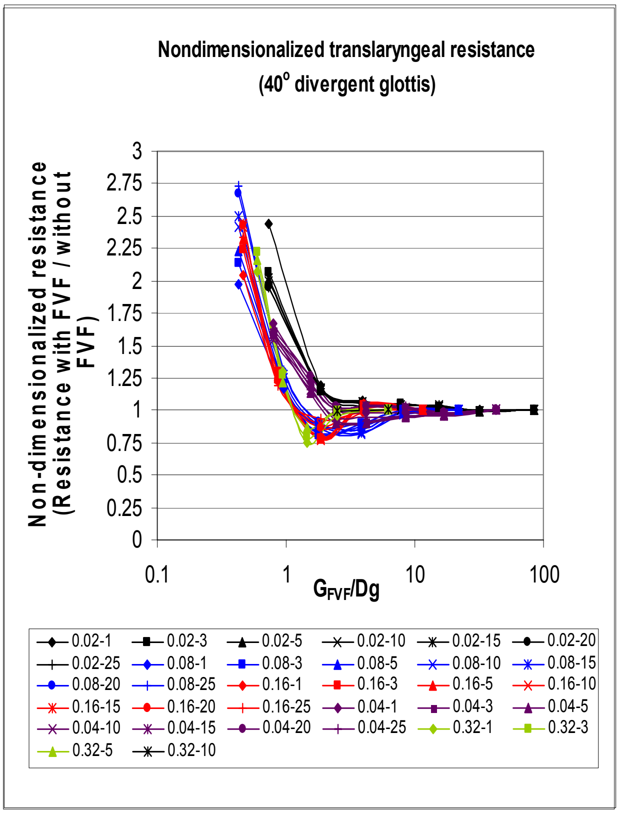

Figure 2: Non-dimensionalized translaryngeal airflow resistance for a 40° divergent glottis relative to non-dimensionalized false vocal fold gap. Each set of colored lines represent a glottal diameter.

3.1. Amount of decrease of non-dimensionalized resistance

The maximum decrease in non-dimensionalized resistance was observed to be about 20-25% for all conditions, although the FVF gap value or normalized FVF gap value for this minimum airflow resistance varied with glottal diameters and angles. The maximum drop in the non-dimensionalized resistance of about 25% was observed for a glottal diameter of 0.32 cm for divergent glottal angles. The amount of lowered resistance decreased from larger to smaller glottal diameters. From Figure 1, it can be seen that glottal diameters of 0.32 and 0.16 cm lowered the non-dimensionalized resistance by about 25% while the non-dimensionalized resistance is lowered by about 15-20% for smaller glottal diameters of 0.08 and 0.04 cm. For a uniform and convergent glottis, the maximum dip of about 25% was seen for a 0.08 cm glottal diameter. The non-dimensionalized resistance was lowered by the same amount with the uniform glottis for other glottal diameters (0.04, 0.16, 0.32 cm) also. For convergent angles, glottal diameters of 0.04, 0.32, and 0.16 cm lowered the resistance by approximately the same amount (15-20%). The glottal diameter of 0.02 cm also helped lower the resistance for the convergent angles to a lesser degree (5-8%).

With respect to the non-dimensionalized false vocal fold gap, minimum airflow resistance for larger (0.08, 0.16, and 0.32 cm) and smaller glottal diameters (0.04 cm) were observed at approximately 2.0 and 2.4, respectively, for most of the data.

Glottal diameters of 0.04 and 0.32 cm showed the greatest variation of airflow resistance across the FVF gap values. Non-dimensionalized resistance variations across pressures were less except for certain conditions like the 40^o divergent glottis.

3.2. Intraglottal pressure distributions

Intraglottal pressure distributions obtained for a few cases showed “more” negative pressures in the glottis for the false vocal fold gaps that result in decrease in the translaryngeal airflow resistance.

3.3. The best fit equation

To get the best fit equation, the data were non-dimensionalized for both the translaryngeal airflow resistance and the false vocal fold gap. The best fit equation was produced by combining two exponential forms. By doing so, major components of the data could be independently controlled. Modifications in the constants were made to get the best fit. The constants, therefore, are either dimensionless or with dimensions of length. The resultant equation is

$$R_{fvf} = 1 + G_1(D_g, X) + G_2(\theta, D_g, X) \quad (1)$$

where,

R_{fvf} = Ratio of non-dimensionalized flow resistance in the presence of the false vocal folds to the non-dimensionalized flow resistance in the absence of the false vocal folds.

X = The ratio of false vocal fold gap and glottal diameter.

D_g = Glottal diameter

θ = Glottal angle { 0 = divergent angle, and 1 = convergent and uniform glottal shapes}

$$G_1(D_g,X) = c_1*\exp[(c_2 + f_1[D_g])*\exp(c_3*X)] \quad (2)$$

$$G_2(\theta, D_g, X) = f_2(\theta,D_g)*\exp[f_3(\theta,D_g)*f_6(D_g,X)] \quad (3)$$

$$f_1(D_g) = c_4*D_g^3 + c_5*D_g^2 + c_6*Dg \quad (4)$$

$$f_2(\theta,D_g) = c_7*D_g^2 + c_8*D_g + c_9*\theta \quad (5)$$

$$f_3(\theta,D_g) = f_4(D_g)*\theta + c_{10} \quad (6)$$

$$f_4(D_g) = c_{11}/(1 + \exp[f_5(D_g)]) \quad (7)$$

$$f_5(D_g) = c_{12}*(D_g + c_{13}) \quad (8)$$

$$f_6(D_g,X) = (c_{14} - f_7(X,D_g))^2 \quad (9)$$

$$f_7(D_g,X) = X + c_{15}*\exp[f_8(D_g)] \quad (10)$$

$$f_8(D_g) = c_{16}*\exp(c_{17}*D_g) \quad (11)$$

$c_1 = 4.5$	$c_2 = -0.33$	$c_3 = 2.0$
$c_4 = -33.541$	$c_5 = 18.639$	$c_6 = -3.2249$
$c_7 = 5.32$	$c_8 = -2.17$	$c_9 = -0.0463$
$c_{10} = -4.5$	$c_{11} = 4.47$	$c_{12} = 225$
$c_{13} = -0.06$	$c_{14} = 1.8$	$c_{15} = 36$
$c_{16} = -1.2$	$c_{17} = 20$	

Essentially, the value of 1 represents the non-dimensionalized resistance when there is no effect of the false vocal folds; i.e., the flow resistance is the same with or without the false vocal folds. This occurs when the false vocal folds are widely placed. Functions G_1 and G_2 modify the value of 1 to a higher or lower value depending on the FVF gap. c_1 through c_{17} are the constants.

The fit is a first approximation to the data. The equation could be further refined to fit all of the data points. The equation seems to fit within 10% for all glottal diameters when averaged across pressure drops except for some obvious data points. For the glottal diameter of 0.02, a maximum error of 13% and 19% was observed for convergent and divergent cases, respectively, for a smaller FVF gap ratio of 0.71. For the glottal diameter of 0.04 cm, a maximum error of 13% (convergent) and 17.5% (divergent) were observed for FVF gap ratio of 1.4. For larger glottal diameters, data within 6% for all divergent cases for the glottal diameter of 0.16 cm could be predicted. Maximum error between 14 and 16% for glottal diameters of 0.08 and 0.32 cm was observed in predicting flow resistances. For convergent and uniform cases, the equation fits within 10% for glottal diameters 0.16 and 0.32 cm, while for the 0.08 cm case, an error of 14% was observed. The average error considering pressure drops of 5, 10 and 15 cm H_2O and non-dimensionalized FVF gap of more than one, for all angles and diameters was 4.7%. The standard deviation was 1.8%.

Some data points were not as well represented as others. For example, data points for divergent glottal angles at a non-dimensionalized FVF gap values of about 1.5 for glottal diameters of 0.02 and 0.04 cm were not well represented. Error in such cases was considerably higher.

4. Discussion

4.1. Effect of the false vocal fold gap.

When the false vocal fold gap was large, the translaryngeal resistance in the presence or absence of the FVFs was the same. This suggests that because the distance between the false vocal folds was so large, the exiting glottal jet did not realize the presence of the false vocal folds and remained unaffected by them.

When the false vocal folds were very close, the FVF gap hinders the path of the glottal flow, dissipating more energy and creating less airflow. It is important to note that when the false vocal fold gap was equal to or smaller than the minimal glottal diameter, the flow resistance through the larynx would increase. The increase in the airflow resistance with the decrease in the false vocal fold gap was not linear. A very small decrement in the false vocal fold gap, below this critical point, can increase the airflow resistance to twice the normal flow resistance of the larynx.

For intermediate FVF gaps, the position of the false vocal folds might be favorable in guiding the glottal jet to retain smooth laminar flow for longer distances, thereby decreasing overall flow resistance. It is well known in fluid dynamics that a spike or forward jet can reduce drag by contouring the free stream about the body, which is known as drafting (Blevins, 1984, pg 346). Also, the angle of the expansion of the false vocal folds has a diverging shape, which corresponds to a diffuser. A diffuser is associated with increase in pressure (pressure recovery) due to the change in area. Pelorson et al. (1995) also reported significant pressure recovery across the false vocal folds due to reattachment of the jet to the FVFs. Flow visualization by Shadle et al. (1991) and Kucinschi et al. (in review) showed that the skewed glottal jet is straightened due to the presence of the false vocal folds. In such cases, straightening the glottal jet lowers the overall resistance of a system as the energy dissipation is less. Moreover, Kucinschi et al. (in review) showed that the glottal jet remains laminar for a longer distance, thereby again reducing the energy dissipation associated with an otherwise turbulent field. Roundedness of the false vocal folds medial edge also is a contributing factor in lowering the overall resistance.

4.2. Amount and range of decreased resistance

The difference in the amount and range of decreased resistance for different glottal diameters and angles can be attributed to a combination of the above mentioned factors and their comparative effect on the viscous and pressure losses which eventually determine the overall resistance. For all glottal diameters except for 0.32 cm, the convergent and uniform glottis show the greatest drop in resistance for the same value of false vocal fold gap. This may be due to significant reduction in kinetic energy loses in the presence of the false vocal folds. A divergent glottis is mainly associated with separation losses that occur due to adverse pressure gradients. Since the false vocal folds are seen to straighten and laminarize the flow (noted mainly for diverging angles - Kuchinshi et al. (in review), Shadle et al., 1991, Pelorson et al., 1995), it would not only reduce dissipation loses above the glottis but also might affect the dynamics of separation points. Kuchinschi et al., (in review) showed that the separation points moved downstream, but not too much, in the presence of the false vocal folds. “Postponement” of the separation in a system also helps to reduce the drag.

4.3. False vocal folds in phonation

The range of the false vocal fold gap reported by Furmanik et al. (1976) and Scherer et al. (1981, 1995) is between 0.6 cm and 0.9 cm. Similar statistics of about 0.54 cm of the false vocal fold gap during phonation was observed in our previous study. Assuming the false vocal fold gap is in the range between 0.5 cm and 0.9 cm, the results suggest that the false vocal folds do not affect the airflow through the larynx during normal phonation (except possibly near the maximum glottal opening). This is because the false vocal folds are placed so wide that their presence is not felt by the high inertia glottal jet (again, except possibly for the greatest glottal diameter). The false vocal fold gap in singers, as reported by Wilson and our previous study, was about 0.4 cm, however. For the false vocal fold gap, the results suggest that the false vocal folds might aid in phonation by increasing the airflow through the larynx during certain periods of vibratory cycle.

During one complete vibratory cycle, the true vocal folds assume converging shapes during its opening phase and diverging shapes during its closing phase. The rectangular shape is rarely seen during the vibratory cycle. When the vocal folds initially open to let some amount of airflow exit, the convergent angle between the true vocal folds may be large with a small minimal glottal diameter. As the opening of the true vocal folds progresses, the glottal diameter increases with a decrease in the angle of convergence between them. Similarly, during the closing phase, the divergent glottal angle will at first be small with a relatively large glottal diameter. As glottal closing progresses, the divergent angle may increase with decrease in the glottal diameter.

In line with the above mentioned possible geometries during a vibratory cycle, let’s consider the shape of the glottis to be 40^o convergent with the diameter between 0.02 and 0.04 cm during the initial opening. As the opening progresses, the glottal shape changes to, say, 20^o convergent with the glottal diameter between 0.16 and 0.32. Similarly during the early phase of the glottal closing, let us assume the glottal shape to be 20^o divergent with the diameter between 0.32 and 0.16 cm. As the closure continues, the glottis takes the shape of a 40^o divergent angle with the diameter between 0.02 and 0.04 cm. From the figures it is noted that during the initial phase of glottal opening, if the false vocal fold gap is about 0.4 cm, the airflow is not affected by the presence of the false vocal folds. However, as the opening progresses, the airflow is increased by about 10-15% (20 c, 0.16 - 0.32 cm). During the closing phase, initially, the airflow is increased by about 20-25% (20 d, 0.16-0.32cm) while towards the end of the closing phase the airflow is increased only by about 5% (40 d, 0.04). If one plots these increased airflow percentages over the normal airflow signal, it will be obvious that the airflow signal with the effect of the false vocal folds increases slowly to a higher peak flow value and decreases sharply for a fixed period of time. This could potentially have favorable acoustic effects on the voice of a singer. Higher peak flow would increase the intensity of the fundamental frequency while the increased slope during the descent ensures more energy in higher partials. Positioning the false vocal folds such that the gap between the two is about 0.4 cm could be an intentional effect learned by the singer to improve both the projection and quality of voice.

On the contrary, with the highly constricted and hyperadducted true and false vocal folds (e.g. FVF gap of 0.2 cm), the false vocal folds seem to aid the entire phonatory cycle. This does not mean that the phonation in such cases is normal, but that the amount of airflow produced is greater than it otherwise would have been. In other words, when the true vocal folds are constricted and allow a certain amount of airflow through, the presence of the false vocal folds might increase this amount of the airflow. This might be one of the reasons why false vocal fold adduction is observed so consistently with hyperadductory glottal pathology.

Zhang et al. (2002) showed that the glottal jet tends to hit the false vocal folds, especially when the true vocal folds are in a diverging shape, creating a dipole source of sound. This produces more energy around the 2.5 KHz region of the sound. Studies on acoustic consequences of the false vocal fold vibration also suggest that higher energy in the 2-6 KHz region is introduced. It is to be noted that the 2-6 KHz region is well within the speech range and would thus affect the quality of voice.

For most glottal diameters and angles, the maximum decrease in flow resistance is observed for a non-dimensional FVF gap of about 2.0 (Figure 2). This translates to a FVF gap value between 0.29-0.48 cm relative to the data of the study. Again, the effect seems to be to increase the airflow through the larynx, and thus reduce energy losses in the larynx. This means that the false vocal folds can aid in phonation by reducing energy losses when positioned appropriately. This concept of positioning an existing structure appropriately to reduce energy losses and increase airflow in the larynx might be important in describing its efficiency. Speaking differently, vocal efficiency is enhanced merely by modifying laryngeal geometry without overloading the true vocal folds, although some work will be done (thus perhaps loosing biological energy) in positioning and maintaining the position of the FVFs. This might be important not only to maintain healthy vocal habits but also to treat ventricular dysphonia.

It is important to note that in ventricular dysphonia, the false vocal folds come very close together and inhibit the flow of air. It is also known that the ventricular dysphonia, or hyperfunctional voice in general, is associated with glottal pathology. It is possible that a patient with glottal pathology has had some success in increasing the intensity of the voice by adducting the false vocal folds.

Lower pressures in the glottis (than observed without the false vocal folds) with increased airflows are also indicative of both biological as well as acoustical efficiency. Increased airflow as discussed above may increase voice intensity and improve quality. With lowered pressures in the glottis, lateral movements of the vocal folds will be less, producing less impact stresses. However, it is important to note that a minimum amount of pressure is necessary for vibration of vocal folds.

5. Conclusions

The effect of the false vocal fold gap on translaryngeal airflow resistance was studied using a Plexiglas model of the human larynx. Various glottal and supraglottal geometries were subjected to seven different translaryngeal pressure drops. Results show that the translaryngeal airflow resistance can decrease as much as 25% for a range of false vocal fold gaps. The amount of decrease in the flow resistance varies with glottal angle and width. A best fit equation predicting the change in the translaryngeal airflow resistance with the inclusion of the false vocal folds is established. The equation error, averaged across glottal diameters, is 4.7% for translaryngeal pressure drops of 5, 10, and 15 cm H_2O and non-dimensionalized FVF gap above one. The results may be incorporated in models of phonation for better understanding of vocal mechanics. The results might also be helpful in exploring surgical and rehabilitative intervention of related voice problems.

6. Acknowledgement

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7. References

[1] Agarwal, M.; Scherer, R.C., and Hollien, H. (2003). The false vocal folds: shape and size in frontal view during phonation based on laminagraphic tracings. Journal of Voice; 17(2): 97-113.

[2] Allen, E.L., and Hollien H. (1973). A Laminagraphic study of pulse phonation. *Folia Phoniatric,* 25, 241-250.

[3] Berg Jw. van den. (1955). On the role of laryngeal ventricle in voice production. *Folia Phoniatrica*, 7, 57 –69.

[4] Blevins, R.D. (1984). Applied fluid dynamics handbook. New York, van Nostrand Reinhold Company Inc.

[5] Fuks, L., Hammarberg, B., and Sundberg, J. (1998). A self sustained vocal-ventricular phonation mode: acoustical, aerodynamic, and glottographic evidences. *KTH, TMH-QPSR*, 3/1998; 49-59.

[6] Furmanik, F., Szczepinska, J., and Biegaj, R. (1976). Relation of Some Dimensions of the Middle Part of the Laryngeal Cavity to span of the Greater Horns of the Hyoid Bone. *Folia Morphologica (Warsz),* 35(2), 123 –131.

[7] Kobayashi, N., and Tohkura, Y. (1989). Acoustic and physiological characteristics of traditional singing in Japan. *The first international conference on music perception and cognition*, 171-174.

[8] Kucinschi, B., Scherer, R.C., DeWitt, K.J., and Ng,T.T.M. (2004). Flow visualization of air moving through a model of the larynx. Journal of the Acoustical Society of America (in review).

[9] Lindestad, P.A., Sodersten, M., Merker, B., and Granqvist, S. (2001). Voice source characteristics in Mongolian “throat singing” studied with high-speed imaging technique, acoustic spectra, and inverse filtering. Journal of the Voice Foundation, 15(1), 78-85.

[10] Nasri, S., Jasleen, J., Gerratt, B.R., Sercarz, J.A., Wenokur, R., and Berke, G.S. 1996). Ventricular dysphonia: A case of the false vocal fold mucosal traveling wave. *American Journal of Otolaryngology*, 17(6), 427-431.

[11] Pelorson, X., Liljencrants, J., and Kroeger, B. (1995). On the aeroacoustics of voiced sound production. 15th International Congress on Acoustics, Trondheim, Norway 26-30 June.

[12] Pinho, S.M.R., Pontes, P.A.L., Gadelha, M.E.C., and Biasi, N. (1999). Vestibular vocal folds behavior

during phonation in unilateral vocal fold paralysis. *Journal of Voice*, 13(1), 36-42.

[13] Rosa, Marcelo de Oliveira, Pereira, J.C. Grellet, M., Alwan, A. (2003). A contribution to simulating a three-dimensional larynx model using the finite element method. Journal of the Acoustical Society of America, 114(5), 2893-2905.

[14] Scherer, R.C. (1981). Laryngeal fluid mechanics: Steady flow considerations using static models. *Doctoral thesis*, University of Iowa, Iowa.

[15] Scherer, R.C., Vail, V.J., and Rockwell, B. (1995). Examination of laryngeal adduction measure EGGW. In: *Producing Speech: Contemporary Issues*. Katherine and Safford Harris (eds); American Institute of Physics, Woodbury, NY: 269-290.

[16] Seeley, B.D. and Young, D.F. (1976). Effect of geometry on pressure losses across models of arterial stenoses. Biomechanics, 9; 439-448.

[17] Shadle, C.H., Barney, A.M., and Thomas, D.W. (1991). An investigation into the acoustics and aerodynamics of the larynx, in J. Gauffin and B. Hammarberg eds. *Vocal Fold Physiology: Acoustic, Perceptual, and Physiological Aspects of Voice Mechanisms*. Singular Publishing Group, Inc. San Diego, 73-82.

[18] Talukder, N., Karayannacos, P.E., Nerem, R.M., Vasko, J.S. (1977). An experimental study of the fluid dynamics of multiple noncritical stenoses. *Journal of Biomechanical Engineering,* 74-82.

[19] van Dreumel, S.C., and Kuiken, G.D.C. (1989). Steady flow through a double converging-diverging tube model for mild coronary stenoses. *Transactions of ASME*, 111, 212-221.

[20] von Doersten, P.G., Izdebski, K., Ross, J.C., and Cruz, R.M. (1992). Ventricular Dysphonia: A profile of 40 cases. *Laryngoscope*, 102,1296-1301.

[21] Wilson, J.E. (1972). A study of the conformation of the laryngo-pharynx in singers during alteration of intensity, frequency, and vowel. *Doctoral thesis,* Indiana University, Bloomington.

[22] Wilson, J.E. (1976). Variations of the laryngo-pharynx in singing. *The NATS bulletin*, 20-22,31.

[23] Zhang, C., Zhao, W., Frankel, S.H., and Mongeau, L. (2002). Computational aeroacoustics of phonation, Part II: Effects of flow parameters and ventricular folds. Journal of Acoustical Society of America, 112/5/Pt. 1: 2147-2154.