An Example of the Role of Basic Science Research to Inform the Treatment of Unilateral Vocal Fold Paralysis

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Abstract

An alternative and complementary approach to randomized trials or other clinical research in unilateral vocal fold paralysis is to use basic science research in animal models to answer the following two questions: (1) how and why do asymmetries affect voice production?, and (2) how do various surgical procedures affect these asymmetries? In this article, we will discuss some of our approaches to the first question. All experiments discussed center around the presence and effects of vortices, or areas of rotational motion, between the folds due to a phenomenon known as flow separation. Therefore, the formation and properties of intraglottal flow separation vortices will be briefly discussed. Then, we will describe experiments that look at the effects of the flow separation vortices on three measures of laryngeal physiology important to voice production: flow skewing, acoustic intensity, and glottal efficiency. Finally, we will explore the effects of some asymmetries on the flow separation vortices and discuss implications for the treatment of unilateral vocal fold paralysis. Our work is early and has some clear limitations. Therefore, the goal of this article is not to fully answer any question, but to show an example of the type of information that can be addressed by research in excised canine larynges.

In unilateral vocal fold paralysis (UVFP), the resting position of the paralyzed vocal fold can vary in a number of ways, depending on the degree of nerve damage and synkinesis (Zealear & Billante, 2006). Most commonly, an asymmetric vocal fold gap is produced by a lateralized axial position of the membranous paralyzed fold, also known as an anterior gap. In flaccid paralysis, the arytenoid may be displaced such that the vocal process is anterior and superior relative to the normal side. Such a foreshortened fold will also be less stiff than the normal fold. This asymmetric tension, or stiffness, is exacerbated if the thyroarytenoid muscle has significant atrophy. The arytenoid may also be displaced laterally, producing a cartilaginous, or posterior, gap. Thus in UVFP, there may be asymmetries resulting in an anterior or anterior and posterior gap, and asymmetries in the length, height, and tension of the vocal folds. For UVFP, treatment options include medialization, arytenoid repositioning procedures, reinnervation, and cricothyroid subluxation. These different procedures affect each of the above asymmetries to differing degrees.

In medialization operations, the membranous vocal fold is pushed toward the midline by an injection procedure or by placement of a permanent implant, thereby closing the membranous glottal gap. Normally, these two procedures will not significantly change vocal fold length, height, or cartilaginous gap. Two main arytenoid repositioning procedures designed to close the posterior gap are arytenoid adduction and adduction arytenopexy. In the arytenoid adduction, reported by Isshiki and Masaki (1978), a suture is attached to the muscular process of the arytenoid and directed anteriorly. Several modifications of Isshiki's description have been reported, but in general the suture simulates the action of the lateral cricoarytenoid and will rotate the displaced arytenoid. On the other hand, adduction arytenopexy (Zeitels, Hochman, & Hillman 1998; Zeitels, Mauri, & Dailey, 2004) is designed to medially translate the arytenoid, rather than rotate it. Neither arytenoid repositioning procedure will eliminate the membranous vocal fold gap. When either arytenoid procedure is performed, a medialization is also usually performed. Reinnervation involves anastomosis of a new nerve (usually the ansa cervicalis) to the paralyzed recurrent laryngeal nerve. Medialization operations will close the vocal fold gap, but will not restore symmetric tone. Reinnervation, on the other hand, has the potential to do both (Crumley, 1990, 1991). Because it can improve muscle bulk and tone of the paralyzed fold, Titze (1979, 1994) noted that reinnervation might be superior to medialization by restoring symmetric stiffness, or, more accurately, "viscoelastic symmetry."

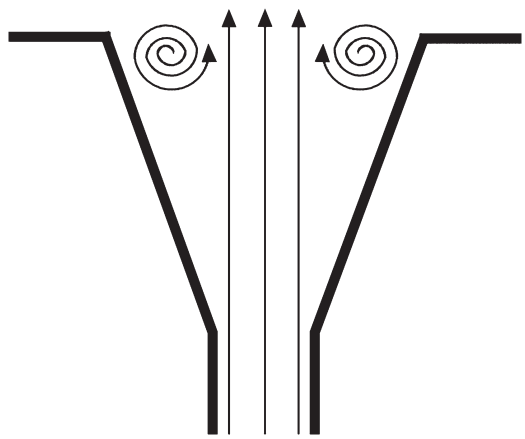
It is clear that a clinician needs to consider many factors in choosing an optimal course of therapy for patients with UVFP. Although there are many papers that demonstrate the efficacy of a particular type of treatment, adequate clinical data supporting the choice of one operation over another is not always available. For example, a reinnervation procedure may address all the asymmetries mentioned above, but as Paniello (1996) writes, "When reinnervation or medialization options are presented to patients with UVFP, there is unfortunately no data presently available to recommend one option over the other" (p. 197) Five years later, this last statement became untrue after publication of a randomized clinical trial comparing medialization and reinnervation (Paniello, Edgar, Kallogieri, & Piccirillo, 2011). This trial showed that for patients under 52 years of age, reinnervation resulted in better perceptual ratings of voice quality than medialization, and that the opposite was true for patients older than 52. Since a randomized clinical trial is commonly believed to be the "gold standard" for determining the most efficacious treatment, the question of what is the best surgical procedure should have been definitively answered. However, while this randomized trial is an impressive feat with fascinating and challenging results, there have been many reasonable criticisms. For example, few of the medialization procedures included an arytenoid adduction. There were also not enough patients to study whether or not the amount of membranous and/or cartilaginous gap mattered. There is currently no good clinical method to measure asymmetries in tension, so the effects of asymmetric stiffness could not be evaluated.

If the optimal procedure is determined by the type and amount of different asymmetries, then the results of this randomized trial may represent the best treatment for only one subgroup of asymmetries. Another criticism is whether or not the most appropriate outcome measures were used. Laryngeal reinnervation resulted in better perceptual measures in the younger group, but medialization produced higher maximum phonation times, which would imply that medialization is better at reducing the glottal gap. For these and many other reasons, controversy remains on the optimal treatment for UVFP.

Intraglottal Flow Separation Vortices

Flow separation describes a phenomenon that is well known in fluid mechanics, in which flow separates from an adjacent wall. Because of the mucosal wave in the vertical (inferior-superior) direction, the shape of the glottis in a coronal plane is different during the opening (folds travelling apart) and closing (folds coming together) phases of vocal fold vibration. During the opening phase of vocal fold vibration, the glottis takes on the shape of a converging nozzle (the superior aspect of the folds is more narrow than the inferior aspect) and the airflow is attached to the entire medial surface of the vocal folds. In this case, the flow separates from the superior surface of the vocal folds at the glottal exit. During the closing phase, the glottis takes on the shape of a diverging nozzle, such that the superior aspect of the folds is wider than the inferior aspect. As the diverging angle of the duct exceeds a certain value, the flow cannot follow the duct walls and will separate from them (Schlichting and Gersten, 2000). This mechanism results in straight flow in the center of the duct and vortices towards the superior-medial aspect of both folds. We refer to the vortices that form between the medial aspects of the folds during closing as flow separation vortices (FSV). The schematic diagram (Figure 1) shows the FSV in a divergent glottal duct, occurring during the closing phase.

Figure 1. Schematic of Flow Separation Vortices Forming in the Divergent Glottis. The Grey Area on top Represents the Space Directly Above the True Folds.



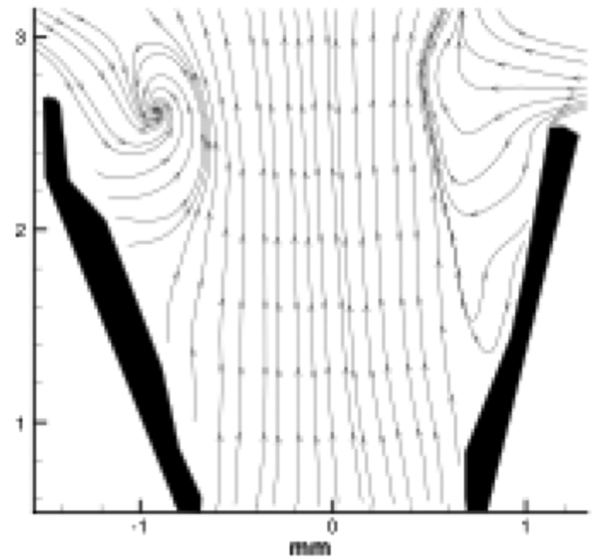
In general, it is known that vortices can produce negative pressures. When the term "negative pressure" is used in this article, we are specifically referring to the gage pressure, or the pressure relative to the ambient pressure. In terms of the force these vortices can exert on the vocal folds, it is the gage pressure that is relevant, not the absolute pressure. Negative pressures will produce an intraglottal suction force on the medial aspect of folds that adds to other forces causing the folds to come together during the closing phase. These negative pressures cannot be determined by analytical and most computational methods, instead requiring very complex, time- and cost-intensive computational methods (Mihaescu, Khosla, Murugappan, & Gutmark, 2010). This is why most theoretical models have not accounted for the pressures associated with the FSV. Additional details on this topic can be found in Khosla, Oren, Ying, & Gutmark (in press).

The mechanism of the FSV will not be described here but can be found in Khosla et al. (in press). However, it is important to note that FSV is not what Bernoulli's law would predict. From the conservation of mass law, the velocity will be highest at the most narrow section of the glottis. During closing, this occurs at the most inferior aspect of the glottis. From Bernoulli's law, high velocities are associated with areas of lower pressure. Thus, use of Bernoulli's law would predict that if negative intraglottal pressures occur during closing, they are present in the inferior aspect of the glottis. However, Alipour and Scherer (2000) showed significant negative pressures in the superior but not inferior glottis during closing. These findings support the hypothesis that the FSV produce negative pressures. To test this hypothesis, we first had to determine methodology to identify and measure the intraglottal vortices.

In our work, we have used excised canine larynges. The vocal processes can be brought together in a variety of ways and airflow through the larynx can cause vibration. In most of our experiments, all tissue above the folds is removed, and the trachea is attached to our airflow. The velocity fields are measured using a technique known as particle imaging velocimetry (PIV). Velocity has a magnitude and a direction, and the term “field” indicates that both components are measured. The direction is especially important for our work, since straight flow will produce significantly different forces and pressures than rotational flow. Imagine the difference between wind flowing in one direction and a tornado. In the PIV method, micron-size particles or droplets are injected into the flow in order to render it visible when illuminated. A laser beam spread into a light sheet using a cylindrical lens produces the illumination. The laser is pulsed such that two sheets are produced microseconds apart. Both images of the illuminated flow field are recorded using a specialized camera. Computer analysis of the resulting images correlates the particles in the two images, allowing a displacement field to be calculated. Because the time between both images is known, a velocity field is calculated. Velocity is equal to displacement/time. The advantage of the PIV technique is that it is noninvasive and can give the spatial distribution. In our earlier work, (Khosla, Murugappan, Gutmark, & Scherer, 2007), only velocity fields above the superior edge of the folds could be measured. Recently, our PIV technique was modified to be able to measure velocity fields between the folds (Khosla et al., in press; Oren, Khosla, & Gutmark, 2014). This technique also allows us to simultaneously determine the medial aspect of the folds. Both intraglottal geometry and velocity fields can be determined during only the closing phase of vibration due to technical limitations of our method. However, this is a minor limitation since the majority of the sound and all of the FSV are produced during the closing phase.

Typically, we measure velocity fields at low, medium, and high subglottal pressures. All pressure values are measured in cm H_2O. The phonation threshold pressure (PTP), or the pressure required to start vibration, is about 7–10 cm for excised canine larynges, over twice of the PTP for humans. “Low” pressures are defined as 1–2 cm above phonation threshold pressure, and would simulate very soft phonation. Figure 2 shows an example of a velocity field for a subglottal pressure of 20 cm H_2O. All fields are taken in the coronal plane at the mid-membranous point, a point halfway between the anterior commissure and the vocal process. The medial aspect of the two thick black lines represent the medial aspect of the folds with the top and bottom edge of the line representing the superior and inferior edge of the fold. The thin lines connect the velocity vectors at those locations, and the arrow indicates the direction of the flow. The closer the lines are together, the higher the velocity. The lines show some rotational (or curved) motion on both sides, but a true vortex is found only on the left side. The rotational motion is also stronger on the left. Further intraglottal velocity fields can be found in Khosla et al. (in press) and Oren et al. (2014). Our experiments have shown that at low subglottal pressures, the glottis is minimally divergent and that there are no or very small FSV. As the subglottal pressure increases, however, the divergence angle increases. From fluid mechanics, it is known that increases in divergence angle will produce stronger FSV, and this relationship has clearly been shown by our experiments.

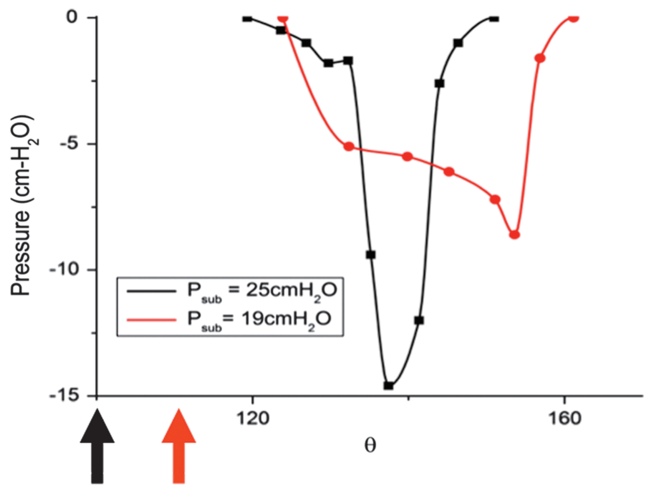
Figure 2. Velocity Streamlines Between the Vocal Folds in a Divergent Glottis During the Closing Phase of the Vibration. The Distance on Both Axes is Measured in mm. The Medial Edge of the Thick Black Lines Represents the Medial Edges of the True Folds.



Using computational methods (Khosla et al., in press), the intraglottal pressures can be determined from the measured velocity fields. We find that the pressures are zero or minimally negative for low subglottal pressures, but routinely range from −10 to −15 cm H_2O for subglottal pressures ranging from 19 to 25 cm H_2O. We also find that the pressures do not change that much in the medial-lateral direction (less than 2 cm H_2O) as they do in the inferior-superior direction (up to a 35 cm difference between the pressures at the superior and inferior edge). This finding is consistent with airflow findings in mechanical ducts and also with complex computational methods (Mihaescu et al., 2011).

Time points in the vibration cycle can be defined by phase, which is measured in degrees. The beginning of opening is given the value of 0 and 360 degrees and is defined when the superior aspect of the folds begins to open. Figure 3 shows the maximum negative pressure at the superior aspect of the folds during closing for two different subglottal pressures. The arrows mark the beginning of the closing cycle, defined as the moment where the inferior edges of the vocal folds start to come together. It is seen that the negative pressures do not occur until the latter part of closing because the divergent shape usually does not form in early closing. The magnitudes and contour of the curves are very similar to those measured in Alipour and Scherer (2000) in a hemilarynx model where half of the larynx is attached to a Plexiglas plate and pressure transducers are placed in the plate. In unpublished experiments done recently, we have used the hemilarynx model to measures pressures, high speed imaging of vocal fold vibration, and measurement of velocity fields during closing. In our experiments so far, the maximal measured negative pressures in the superior half of the glottis have ranged between −11 and −15 cm H_2O for subglottal pressures between 20 and 25 cm H_2O, values consistent with our previous experiments in larynges with both folds. The advantage of our computational method over the hemilarynx direct measurements is that a larynx with both folds is used, the pressures are measured across the entire width and at more vertical locations, and we can show that the negative pressures are due only to the vortices. Other investigators have proposed that negative intraglottal pressures can be caused by vocal tract inertance (Fant, 1983; Titze, 1988), but this is not a factor in our experiments since the vocal tract is removed.

Figure 3. The Lowest Negative Intraglottal Pressure in the Superior Aspect of the Fold During the Closing Phase. The Arrows Mark the Beginning of the Closing Phase.



While we clearly show the existence and mechanism of these negative pressures, the question is whether or not the FSVs have any effect on vocal fold vibration and the resulting acoustic signal. Many theoretical and computational models show FSV are not a requirement for vocal fold vibration, so why should we care about FSV? A potential answer can be found by looking at the volumetric flow rate and a specific phenomenon known as flow skewing.

Mechanisms of Increasing Maximum Flow Declination Rate

Though there may be multiple minor sources of sound, most of the acoustic energy at the glottal exit is produced by flow modulation (Fant, 1960) where "flow" refers to the volumetric flow rate (Q) produced at the glottal exit during the phonation cycle. Q is described in terms of a volume of air traveling through the glottal exit per a given unit of time, such as cm^3/sec, and is also known as the volume velocity. Flow modulation refers to the fact that the Q is changing during the vibration cycle. Although Q increases during opening and decreases during closing, the volumetric flow rate rapidly decreases during the latter part of closing. The majority of acoustic energy is produced during this closing of the vocal folds, and can be measured by a quantity known as maximum flow declination rate (MFDR). MFDR is highly correlated with vocal intensity (Gauffin & Sundberg, 1989; Holmberg, Hillman, & Perkell, 1998; Sapienza & Stathopoulos, 1994; Scherer, Sundberg, & Titze, 1989; Sundberg & Gauffin, 1979). Stevens (1998) noted that the rapid reduction of flow is also important for generating acoustic energy over a broad frequency range and showed analytically that increasing the rate of flow shutoff will produce increased energy in the higher harmonics, a theory supported by multiple findings in patients (Hanson, 1997; Klatt & Klatt, 1990). This finding is clinically important because decreased higher harmonics can result in reduced speech intelligibility. Thus, it is important to determine the underlying mechanisms that contribute to controlling MFDR.

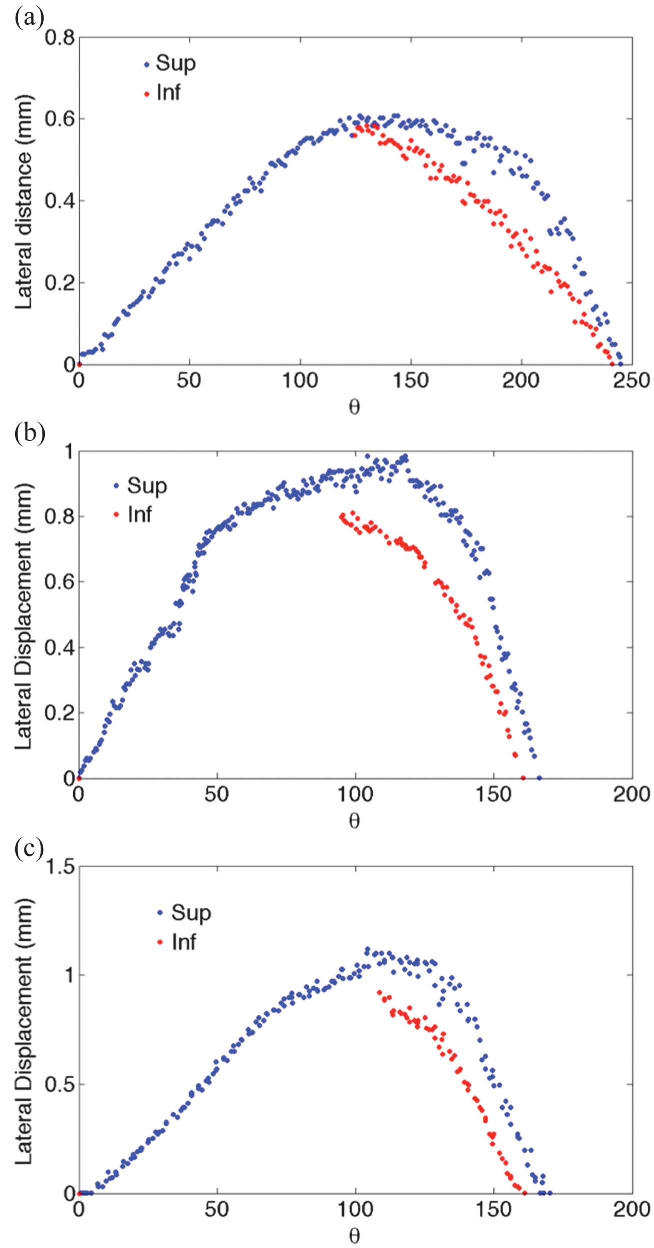
The fact that Q decreases at a much more rapid rate than it increases is known as skewing of the flow rate curve to the right, or usually just flow skewing. Skewing of the volumetric flow rate waveform to the left would mean that Q increases more rapidly than it decreases and no skewing would mean that the Q waveform is symmetric (it rises and decreases at the same rate). In the case of phonation, the volumetric flow rate is equal to the area between the superior edge of the folds and the velocity of the airflow exiting the glottis. Thus, MFDR will be determined by maximal area declination rate (MADR) and the maximum velocity declination rate (MVDR).

Clinically, MFDR is derived from the volumetric flow rate waveform. The latter is most commonly measured by a technique known as inverse filtering (Rothenberg, 1973). In this technique, the volume velocity is first directly measured at the mouth and then a calculation using a standardized transfer function for the vocal tract is performed to derive the flow rate at the glottal exit. This technique has been used in multiple clinical studies showing general agreement with theoretical models (Holmberg et al., 1988; Klatt & Klatt, 1990). However, this technique is an indirect calculation of the glottal volume velocity, as opposed to a direct measure, and results can be difficult to correctly obtain and interpret (Javkin, Antonanzas-Barroso, & Maddieson, 1987). In addition, in order to validate the method of inverse filtering or determine the accuracy, the method needs to be compared to a direct measurement of the volumetric flow rate at the glottal exit in a human or animal model.

Verneuil et al. (2003) simultaneously measured velocity and corresponding glottal area for multiple time points in the phonation vibratory cycle. The glottal area was measured using videostroboscopy, and the velocities were measured one centimeter above the glottis using one-dimensional hot-wire anemometry. Although the work of Verneuil et al. (2003) represents the most advanced published measurements of glottal flow, there are a few important limitations to this work. First, the hot wires were not able to be placed directly at the glottal exit, due to the risk of damaging the probe, but were located 1 cm above the fold instead. Our previous work (Khosla et al., 2007; Khosla et al., 2008) shows that the velocity field 1 cm above the glottal exit is significantly different than that at the glottal exit. The second major limitation is that current two-dimensional videostroboscopy or even high-speed videography most accurately determines the edge of the air/vocal fold interface at the minimum glottal area (Deliyski et al., 2008). In the case of closing, the minimum glottal area is at the inferior edge since the glottis is divergent. For multiple reasons, the waveform of the area at the glottal exit (superior edge) may not be similar to the waveform at the inferior edge.

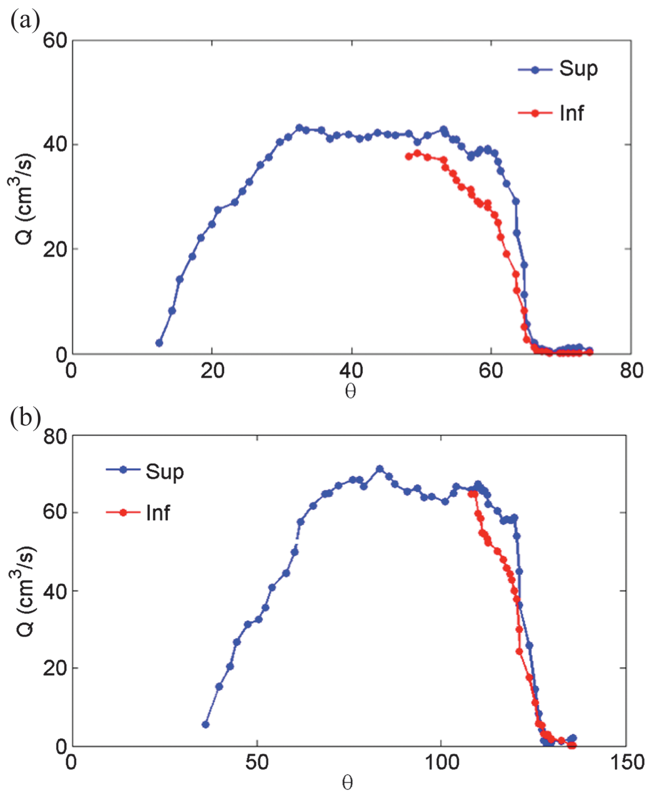
Our current PIV measurements can accurately determine the distance between the superior and inferior aspect of the folds in the mid-membranous coronal plane during closing. Since the length of the glottis is fixed throughout the cycle, the glottal area will be proportional to the mid-membranous distance between the folds. The exception to this is when there is an anterior-posterior zipper-like mucosal wave so our technique is only valid when vibration is symmetric relative to the anterior-posterior axis. Figures 4a, 4b, and 4c show examples of how the distance between the folds at the mid-membranous location changes as a function of phase. Waveforms for a low, medium, and high subglottal pressure are shown. The distance between the inferior edges during opening cannot be measured due to technical limitations of our methods, but it can be seen that the curves during closing are mildly different and that waveform at the superior edge (which is proportional to the area waveform) skews more to the right as subglottal pressure increases.

Figure 4. The Distance Between the Superior and Inferior Edges of the Folds at the Mid-Membranous Location as a Function of Phase for (a) Low, (b) Medium, and (c) High Subglottal Pressure.



In unpublished work, we also observed that the velocity waveforms skew to the right and that the skewing increases as the subglottal pressure increases (not shown in figure). Since it has been shown that the velocity waveforms along the anterior-posterior axis are symmetric (Alipour & Scherer, 2000; Verneuil et al., 2003), the resulting flow rate curves that we measure by multiplying the velocity and distance waveforms will be proportional to the total flow rate. Since these flow rates are for a 1 mm thick (the thickness of the laser light sheet) cross section in the mid-membranous coronal plane, the measurements of Q from our PIV techniques will be referred to as planar flow rates. Figures 5a and 5b show the planar flow rate at low and high subglottal pressures, respectively. It can be seen that the waveform is more symmetric at the low subglottal pressure and more skewed to the right at the high subglottal pressure. It can also be seen that the MFDR is much higher for the high subglottal pressure. Using measurements from 6 excised canine larynges, we have a found a statistically significant relationship between the strength of the vortices and both the MFDR and the amount of skewing of the flow rate waveform. Our comprehensive flow rate data is unpublished, but we are currently finalizing the manuscript.

Figure 5. The Flow Rate as a Function of Phase at the Inferior and Superior Edges of the Folds as a Function of (a) Low and (b) High Subglottal Pressures.



An important question is what mechanisms, in the experiments described above, are responsible for the increase in MFDR, MVDR, and MADR, and for the skewing of the area, velocity, and flow rate waveforms. There have been a few proposed mechanisms for increasing MADR. Since the length of the folds is usually fixed during the vibration cycle, the reduction of area is determined by how quickly the superior edges of the fold come together, which we define as the maximum vocal fold closing speed (MVFCS). One hypothesis is that increasing maximum lateral displacement (MLD) increases MVFCS. The proposed mechanism is that increasing MLD will increase the elastic recoil forces, which will increase vocal fold closing speed. While this may result in an increase in MADR, it will not explain skewing of the distance waveform seen in Figures 5b and 5c. Another theoretical model shows that skewing of the area curve to the right may occur if the superior aspect of the fold is stiffer than the inferior aspect (Titze, 2006). However, actual measurements in excised canine larynges (Oren, Dembinski, Gutmark, & Khosla, in press) and human larynges (Chhetri, Zhang & Neubauer, 2011) show that the opposite is actually true: the inferior aspect of the fold is stiffer than the superior aspect. As described previously, the vortices can cause an increase in closing speed by providing an additional suction force on the superior aspect of the glottis. Note that the vortices are not found in the inferior aspect. Therefore, skewing of the area curve at that location is not expected, which is why it is important to measure area at the glottal exit.

Theoretical models hypothesize that skewing of the velocity and volumetric flow rate can be caused by vocal tract inertance (Titze, Riede, & Popolo, 1988), which is increased by vocal tract constrictions such as those seen in semi-occluded vocal tract (SOVT) therapy (Titze et al., 2008; Titze & Story, 1997). The positive effects of vocal tract inertance and SOVT on MFDR and flow skewing cannot be overstated and are especially important for voice therapy. However, a vocal tract is not used in our model, so another explanation is needed. For complex reasons not described here, the vortices will produce the velocity skewing. Thus, the FSVs are responsible for the skewing of the area and velocity waveforms, and thus the flow rate waveform. Increasing the FSV will increase MFDR, and therefore the acoustic intensity. In unpublished data, we have also seen a strong statistical relationship between the vortex strength, the subglottal pressure, and sound pressure level (SPL).

Increasing the MVDR and the MADR will have different effects on the collision stresses of the vocal folds. Since the velocity of the airflow is mostly parallel to the medial edge of the folds, increasing the MVDR will not cause increased trauma to the folds during vibration. Increasing MADR, on the other hand, is associated with increased vocal fold closing speed, which will increase vocal fold trauma. Thus, the positive effects of the vortices on MVDR result in increased acoustic intensity without increased vocal fold trauma, which is especially important for singers and professional voice users.

Another role of the vortices in reducing vocal fold trauma and vocal effort can be explained by the following example. Suppose we are driving two larynges at the same subglottal pressure and that in the first larynx, the vocal folds have zero divergence angles during all of closing, while a high divergence angle is attained during closing in the second larynx. Because of the additional suction force produced by the vortices and the positive effects on MADR and MVDR, the second larynx will have a much higher MFDR then the first, resulting in higher acoustic intensity or higher SPL. If the ratio of SPL over subglottal pressure is defined as glottal efficiency, the second larynx is much more efficient due to the effects of the FSV.

In terms of vocal fold trauma, it will take much more subglottal pressure for the first larynx to get a SPL equal to the second larynx. This increase in subglottal pressure will increase maximum lateral displacement, which will increase the closing speed by increasing the elastic recoil forces, and this results in increased vocal fold trauma. Thus, without the divergent shape, reduced glottal efficiency results either in a softer voice or increased trauma to the folds in an effort to get a louder voice. In this example, having a straight glottis eliminated the FSV. However, any condition that causes decreased FSV will cause the detrimental effects described above, which are described in the next section.

Clinical Implications

As discussed in the last section, it is important to determine conditions that cause decreased flow separation. We have previously described a case of asymmetric vocal fold stiffness that resulted in periodic vibration with amplitude but not phase asymmetry (Khosla, Murugappan, Lakhamraju, & Gutmark, 2009) and asymmetric stiffness produced by unilateral vocal fold scarring (Murugappan et al., 2009). The results were that FSV were dramatically reduced in both cases. However, it was noted that increasing subglottal pressure produced some increases in the flow separation vortices.

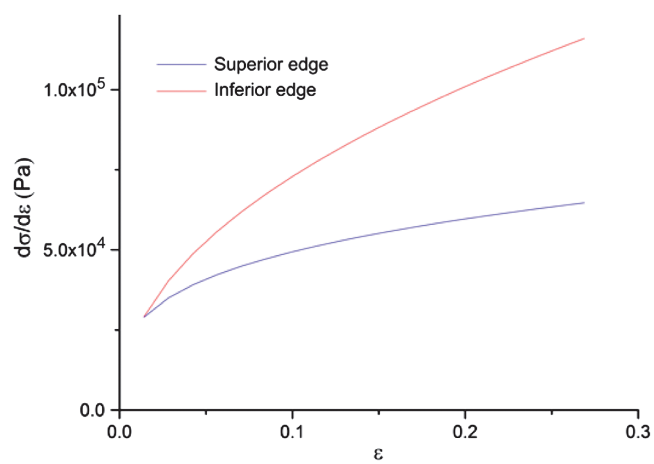
We have also seen reductions in the FSV in cases of asymmetric length, and asymmetric left-right axial position of the vocal processes. As discussed previously, all three of the above mentioned asymmetries could occur in UVFP. Thus, so far we can say that these asymmetries can result in reduction of divergence angle, FSV, SPL, and glottal efficiency. It is extremely important to note that the effects on SPL may not be noted clinically since increases in subglottal pressure (and probably in vocal tract inertance) can increase SPL. The main difference with reduced FSV will be glottal efficiency. It will take more subglottal pressure to produce the same

SPL, which will cause increased glottal effort and increased vocal fold trauma. The increased glottal effort will be manifested by increased vocal fatigue and often generalized fatigue. Both glottal efficiency and vocal fatigue are hard to quantify. The latter can be determined qualitatively, but may be due to several factors. Using aerodynamic measures in the clinic, glottal efficiency can be approximated, and it may be worth looking at this for cases of vocal fold paralysis. This change in glottal efficiency is due to an altered vertical configuration of the glottis, which can be qualitatively but not quantitatively evaluated by current imaging methods (either videostroboscopy or high speed imaging).

Experiments are currently being done using medialization alone (with a silastic implant) and medialization plus arytenoid adduction. Results of two experiments show that medialization +arytenoid adduction results in greater divergence angles, stronger FSC, and increased glottal efficiency compared to medialization alone. In these experiments, the only asymmetry is in the left-right axial direction and there is a significant membranous and cartilaginous gap. However, two cases are not enough to draw significant conclusions. The effects on the FSV are expected to be less dramatic for small membranous gaps only, but these experiments need to be done.

Another factor to consider is the effect of subglottal medialization on the FSV and resulting acoustics. Anecdotally, many laryngologists believe that medializing the subglottis is beneficial, but the mechanism has not yet been clearly shown. Looking at the stress-strain relationships in the excised larynges can identify a possible mechanism. We have done this by using an indentation method (Chhetri et al., 2011) that displaces the fold in the lateral direction at the superior and inferior aspects of the fold. Figure 6 shows the results for one excised canine larynx. A measure of stress is shown on the y-axis and a measure of displacement is shown on the x-axis. At low displacements, it can be seen that the stiffness is equal, but at higher displacements it can be seen that the inferior edge is much stiffer than the superior edge. This difference in stiffness would produce a greater divergence angle at higher subglottal pressures, which is what we have seen in our previously described experiments. These experiments are further described in Oren et al. (in press). Both have proposed that these differences in stiffness are due to the effects of the conus elasticus on the inferior edge. At low displacements, the conus may not be significantly stretched, but at high displacements, stretching of the conus should result in much greater stiffness. Thus, we propose that medializing the subglottis will stretch the conus and thus result in greater inferior stiffness, which will result in a greater divergence angle as subglottal pressure increases.

Figure 6. Stiffness vs. Strain for the Inferior and Superior Aspect of the Vocal Fold. As Strain Increases, Displacement Will Increase.



The limitations of this work are multiple. The canine larynx has different vocal fold properties than human larynges. Our experiments do not include a vocal tract, the flow fields are two-dimensional, and the muscles are not stimulated. On the other hand, the divergence angle and vertical stiffness gradient seen in the canine larynges also occur in humans. Preliminary vocal tract experiments show that vocal tract constrictions actually increase the flow separation vortices. We are currently completing more experiments with asymmetric conditions and with different surgical procedures. In the near future, we are using three-dimensional particle imaging velocimetry to obtain complete flow rates. In the next few years, we plan on looking at the effects of muscle stimulation on FSV. Nonetheless, there is information that can only be obtained clinically or by other models, such as computational or mechanical models. This is why UVFP, and many other voice disorders, are best studied using a variety of approaches.

Conclusion

Clinical experiments alone may not give us comprehensive algorithms to treat all of the various combinations of structural asymmetries that can present in UVFP. We have shown very strong evidence that in the case of excised larynges without a vocal tract, increased subglottal pressure will produce an increased divergence angle, which will produce increased FSV. The FSV will result in increased MFDR, flow skewing, acoustic intensity, and glottal efficiency. Prior to our work, it was thought that only increasing vocal tract inertance would cause these effects. Although the effects of the vocal tract are extremely important, structural asymmetries are unlikely to affect tract inertance, but likely, as our preliminary work suggests, to reduce the FSV. We propose that further work addressing the effects of different procedures for UVFP on divergence angle and FSV will give us significant and new insights on how to surgically treat UVFP.

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