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How Does the Absence or Presence of Subglottal Medialization Affect Glottal Airflow?

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Objectives: Our previous work has shown that the symmetric, smooth, convergent shape of the subglottis reduces turbulent airflow at the glottal entrance. Medialization thyroplasty may alter the glottal shape and is very likely to introduce some degree of glottal asymmetry, which could result in increased turbulence and a reduction in voice quality. This study reports the effects of medializing and not medializing the subglottis in silicone models of human cadaveric larynges.

Methods: In experiment 1, silicone models of 4 human cadaveric larynges were created. The subglottis was then completely medialized in all 4 models. Hot-wire anemometry was used to measure velocity and turbulence profiles at the entrance and exit of the subglottis. In experiment 2, 1 model was created to accommodate incremental medialization of the glottis without any medialization of the subglottis. Airflow characteristics were likewise measured.

Results: In experiment 1, the average maximum turbulence intensity (TI) at the exit of the larynx was less than the TI of incoming tracheal airflow for all 4 larynges. In experiment 2, incremental medialization of the glottis did not affect the TI for medialization up to 35%. However, the TI significantly increased for medialization of 53%.

Conclusions: Medialization of the subglottis does not significantly affect the turbulence reduction properties of the subglottis, even though subglottal asymmetry is introduced. On the other hand, large amounts of medialization of the glottis only (with no subglottal medialization) can introduce significant amounts of turbulence.

Key Words: larynx, phonation, vocal fold, voice.

INTRODUCTION

Medialization thyroplasty represents the most common and effective phonosurgical procedure for improving voice in patients with unilateral vocal fold paralysis (UVFP).[1-4] Some authors have proposed medialization techniques that allow subglottal augmentation,[5] whereas other techniques medialize the glottis only. A better understanding of how the absence or presence of subglottal medialization affects the voice may allow surgeons to optimize this procedure, as well as offer insight into voice production in general. The phonatory role of the subglottis has not been described in current theories of voice production.[6-8] However, our previous work in excised canine larynges showed that turbulence was significantly reduced in the subglottis, specifically because of the smoothly converging shape of the subglottis. This report looks at how specific changes in the smoothly converging shape affect turbulence reduction.

Glottal airflow during phonation can be separated into coherent and random components. Khosla et al[9] have shown that a variety of coherent, highly repeatable flow patterns (vortices) are produced within the first centimeter above the glottis. These vortices can produce acoustic energy in narrow frequencies, thus contributing to harmonics. The random component of glottal airflow, however, produces energy over a broad range of frequencies. As the random component of the glottal airflow increases, so does the "broadband noise," reducing the harmonics-to-noise ratio (HNR). Increased turbulence (a measure of random airflow) is important clinically because it can result in a decreased HNR, an abnormal voice,[10] breathiness,[11] and chaotic (irregular) vocal fold vibrations.[12]

As mentioned previously, recent work in our laboratory suggested that the subglottis functions to reduce random flow, or turbulence, as air passes from the trachea to the vocal folds.[13] In the cited study,

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hot-wire anemometry was used to measure the turbulence intensity (TI) of airflow in excised canine larynges. Turbulence intensity is a measure of airflow that is not related to coherent flow patterns, but increases with the random component.[14] By measuring TI at a subglottal plane and comparing this to the TI 2 to 3 mm above the glottal exit, we found that the random component of glottal airflow is significantly reduced as it passes through the subglottis.

The turbulence-reducing property of the subglottis is due to two factors. The first factor is the area reduction ratio (ARR), which is a measure of how much the cross-sectional area of a converging duct is reduced. The utilization of ARRs, or contraction ratios, to decrease turbulence is widespread in the designing of low-speed wind tunnels.[15] Hussain and Ramjee[16] suggested that a contracting nozzle whose flow area constricts rapidly is effective in suppressing turbulence. Ramjee and Hussain[17] found that the TIs at the nozzle exit for a given contraction ratio were independent of the initial TIs. It was also noted that the TI decreases rapidly with increasing ARR and reaches a minimum for an ARR of 45, after which it increases slowly. When the folds are in the adducted prephonatory condition, the ARR is large, and turbulence will be reduced by this mechanism. It is important to note that as long as the prephonatory glottal width does not change, the presence or absence of subglottal medialization will not affect the ARR.

The second factor is the smoothly converging shape of the subglottis. Principles of fluid dynamics teach that the shape and contour of a duct also play a role in turbulence production. Uneven contours, or ledges, in a converging duct result in abrupt changes in cross-sectional area. Durst and Loy[18] found that sudden contractions in the cross-sectional area of a pipe were associated with increased pressure losses, thought to be due to turbulence-generating sources occurring at the ledges. Additionally, asymmetric duct shapes are more prone to fluid dynamic instabilities. Such instabilities also lead to turbulence generation.

These two theories may influence voice production in patients with UVFP. In most patients with a paralyzed vocal fold, the ARR decreases because of a glottal gap, resulting in higher levels of turbulence. It would be expected, therefore, that patients with UVFP have increased turbulence, a decreased HNR, and increased breathiness. Hartl et al[19] reported a decreased HNR in patients with UVFP. Medialization thyroplasty has been show to increase the HNR and decrease breathiness[20,21]; part or all of this change may be due to the effect of medialization thyroplasty on increasing the ARR.

Medialization thyroplasty results in a reduction of the asymmetry of the membranous glottis, whereas other operations, such as arytenoid adduction, may reduce the asymmetry of the cartilaginous glottis. Although the value of reducing these glottal asymmetries is well accepted, the importance of reducing subglottal asymmetry is largely unknown. Medialization techniques that alter the subglottal shape may introduce ledges into the otherwise smooth subglottis. These ledges could increase the turbulence of airflow entering the glottis, thereby adversely affecting the voice quality. It is important to note that the change in ARR is not dependent on medialization of the subglottis, so our purpose here was only to study the effects of the change in the shape.

It is unlikely that any medialization of the subglottis will completely restore the smooth shape of the subglottis. Therefore, we used 2 experiments that roughly estimated the extremes of subglottal medialization. In the first experiment, the membranous and cartilaginous glottis was medialized in such a way as to mimic normal prephonatory adduction; in this "before" case, there was both glottal and subglottal symmetry. In the "after" case, the subglottis was completely medialized such that the inferior and superior aspects of the conus elasticus were at midline in the axial plane. Theoretically, this complete medialization of the subglottis introduced a step at the junction of the subglottis and trachea; however, the actual angle of that step depended on the material properties of the subglottis and trachea. This angle was qualitatively evaluated. In the second experiment, the glottis was incrementally medialized without any medialization of the subglottis. This absence of any subglottal medialization introduced a ledge at the inferior edge of the medialized fold; again, the shape of this ledge was qualitatively evaluated.

METHODS

For both experiments, silicone models of human cadaveric larynges were created. The principle of using laryngeal models to study glottal airflow is not new.[22] There are several advantages of using models in the current study. First, hot-wire anemometry requires continuous airflow to be passed through the larynx. Cadaveric specimens often dry out in such conditions, altering hot-wire measurements. Additionally, keeping the specimens sufficiently moist for measurement increases the risk that laryngeal fluids will contaminate the hot-wire, decreasing the accuracy of velocity measurements. Moreover, models can be saved and reused multiple times. This is

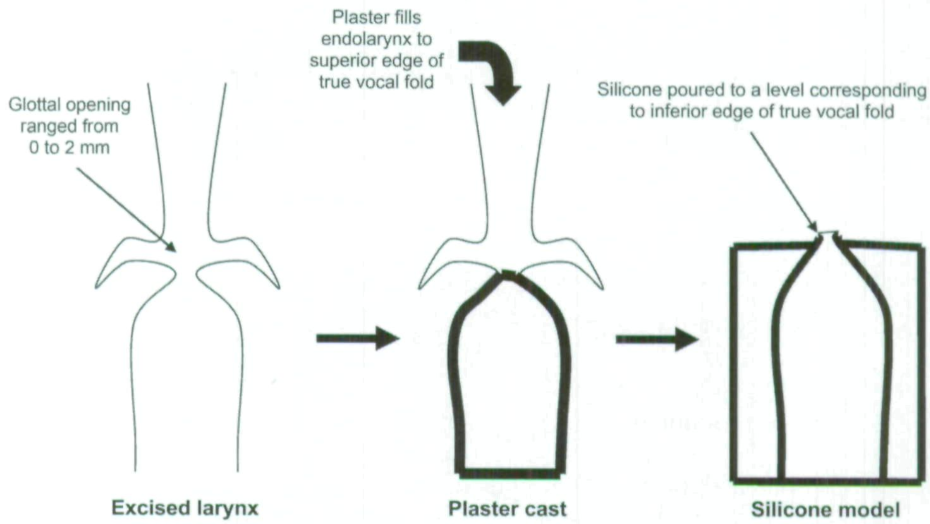

Fig 1. Schematic diagram outlining steps of model creation.

not true for cadaveric specimens, which decompose after about 5 to 7 days.[22] Using models provides a more controlled measurement environment and allows repeat experiments on the same specimen, if needed. The disadvantages of using models include 1) the introduction of additional human error as the models are created and 2) the introduction of a nonorganic substance (silicone elastomer) whose physical properties are not identical to those of laryngeal mucosa.

EXPERIMENT 1

Four excised human larynges were harvested from cadavers identified as organ donors. Three cadavers were male, and 1 cadaver was female. The specimens were kept in a saline bath (0.9% sodium chloride) and refrigerated when not used. All model creation and surgery was accomplished within 72 hours of harvest.

Silicone Models. Figure 1 is a schematic diagram of the model creation. An excised human cadaveric larynx was mounted on an aluminum pipe covered with a plastic cap. An 8/32 screw was placed halfway through the cap so that it protruded approximately 2 cm from the top of the cap. The larynx was held in space with double prong pins on each side, and the base of the larynx was secured with a 5-mm tube clamp. In excising the larynx, 3 cm of trachea was included in the specimen. The inferior 1 cm of the trachea was mounted on the pipe. Using methods previously described, we medialized the membranous folds and the arytenoid cartilages.[9] The mounted specimen was then placed on a vibrating table, and plaster (QuickStone, Whip Mix Corporation, Louisville, Kentucky) was injected into the endolarynx with a 60-mL syringe. After adequate time for settling on the vibrating table, the plaster was allowed to harden. The larynx was removed, resulting in a plaster cast of the endolarynx that extended from the superior edge of the vocal folds superiorly to 2 cm below the cricoid cartilage inferiorly. The screw placed in the plastic cap was embedded in the inferior 1 cm of the cast.

The screw extending inferiorly from the cast was screwed into a flat base with a hole drilled in the center. A polyvinyl chloride pipe (inner diameter, 2.0 inches; outer diameter, 2.25 inches) was placed over the cast such that the cast extended into the center of the pipe. Screws and elastic bands held the pipe in place. VST-30 platinum silicone elastomer (Factor II, Inc, Lakeside, Arizona) was mixed with the appropriate catalyst and poured into the pipe. The silicone elastomer filled the pipe to a level on the cast corresponding to the inferior edge of the vocal fold. Thus, the superior edge of the silicone model corresponds to an axial plane through the most superior aspect of the subglottis, at the inferior edge of the vocal fold. Because the glottis was fully medialized in the "before" and "after" cases, we wanted to measure the turbulence at the glottal entrance (inferior aspect of vocal folds).

The silicone was permitted to set, at which time the pipe was removed by separating it into 2 segments. (The pipe had been cut longitudinally beforehand.) The cast was then removed, resulting in a silicone model of the larynx that extended from the inferior edge of the vocal fold superiorly to 2 cm below the cricoid cartilage inferiorly (Fig 1). Models were created for all 4 specimens before and after medialization thyroplasty, resulting in 8 models.

Medialization of Subglottis. A 5 × 10-mm cartilage window was created in the right thyroid ala, leaving a 4-mm cartilage strut below the window. The medial edge of the window started 5 mm from midline. The inner perichondrium was not preserved. A

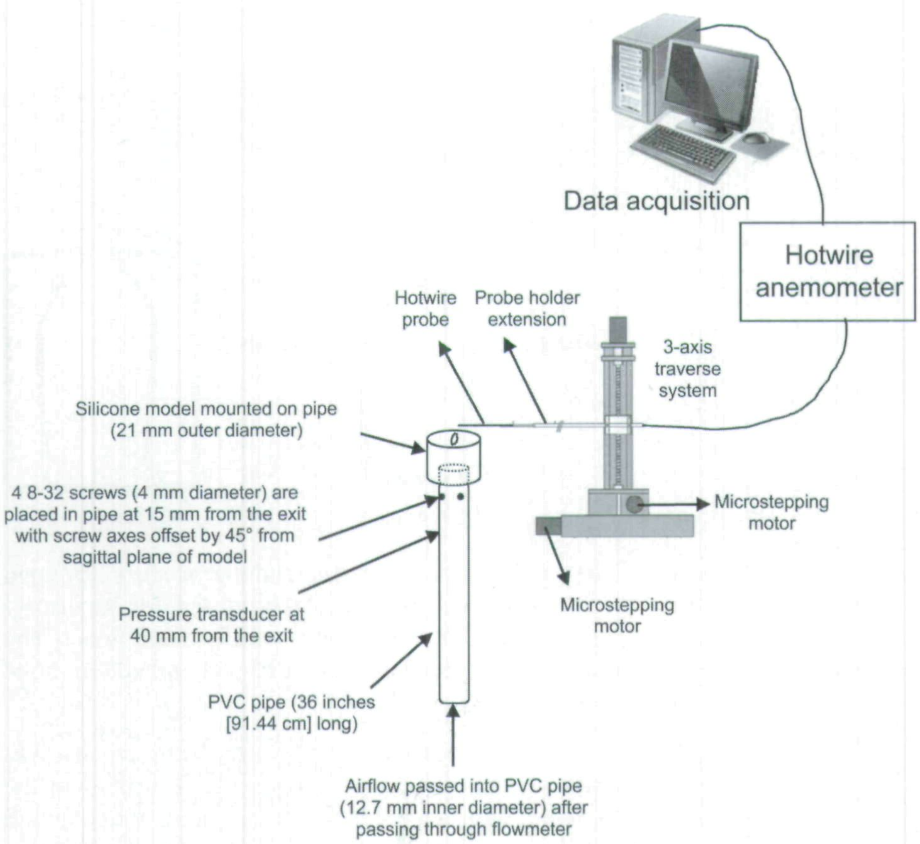

Fig 2. Schematic diagram of complete experimental setup. This hot-wire anemometry method was used to measure velocity and turbulence profiles in experiments 1 and 2. OD — outer diameter; ID — inner diameter; PVC — polyvinyl chloride.

carved silicone block was then placed through the window into the paraglottic space with a 5 × 10-mm tab left in the window to keep the block secure. Because the glottis was already medialized, the purpose of the block was to completely medialize the subglottis. The block was carved such that the entire subglottis was at midline; the glottis and subglottis were visually inspected to ensure medialization to the midline.

Hot-Wire Anemometry. Turbulence intensity is defined as the percentage of the root mean square (RMS) of the flow fluctuations relative to the maximum flow velocity[14] (U' = RMS velocity; U_{max} = maximum velocity). To increase the turbulence of airflow entering the models, we inserted four 8/32 screws 3 cm below the superior edge of a 36-inch pipe (inner diameter, 12.7 mm; outer diameter, 21 mm). The screws were placed at 90° around the circumference of the pipe, offset 45° from the sagittal plane of the glottal exit. The upstream end of the pipe was connected to tubing that provided the air source. A mass flowmeter and control valves were used to regulate the air upstream. Figure 2 is a schematic diagram of the entire experimental setup.

A hot-wire anemometer (AN-1005, AA Lab Systems, Ltd) was used to measure the TI. Calibration between 0 and 50 m/s was performed by fitting a fifth-order polynomial between the hot-wire voltage output and the known velocity measurement from a regulated jet. This velocity range was sufficient to cover all expected velocities in the tests. The signal from the hot-wire was digitized and recorded with a LabV computer equipped with a National Instruments high-speed multifunction PCI-6259 data acquisition card. The hot-wire was checked periodically for contamination. If it was found to be contaminated, it was cleaned with an alcohol solution and recalibrated before measurements were taken.

Baseline measurements, without the model, were taken 2.5 mm above the exit of the pipe. These measurements represent tracheal airflow just below the cricoid cartilage. The model was then placed on the pipe and secured with a 12-mm hose clamp. Mean and turbulent velocity profiles were obtained for all 8 models by traversing the hot-wire 2 to 3 mm above the superior plane of the models in the posterior, medial, and anterior planes. The medial plane was measured halfway between the anterior and posterior edges of the glottal opening (on the model). The anterior plane was measured halfway between the anterior edge of the glottal opening and the middle plane. The posterior plane was similarly measured posteriorly. Fine-step measurements were taken at 0.1 mm intervals with a motorized traverse system (BiSlide and VXM motor, Velmex Inc, Bloomfield, New York). Special care was taken to ensure that

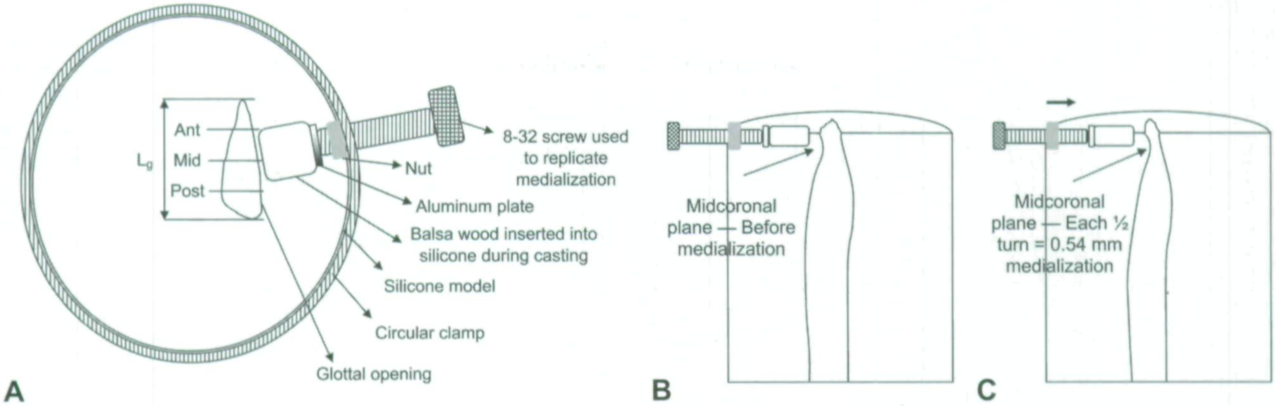

Fig 3. Schematic diagram of experimental setup for incremental medialization (experiment 2). **A**) Top (axial) view of silicone model. **B**) Coronal view before medialization. **C**) Coronal view after medialization. L_g — glottal length; Ant — one quarter of L_g (measured from anterior edge of glottal opening); Mid — one half of L_g (measured from anterior edge of glottal opening); Post — one quarter of L_g (measured from posterior edge of glottal opening).

the measurements at each trial were done along the same axes and at the same height. We took 100,000 data points at each location at a sample rate of 25 kHz.

All statistical calculations were done in Matlab 7.0 (The MathWorks, Natick, Massachusetts). The data were imported into Matlab and processed to find the mean and RMS for each measurement point. Fitting curves and confidence levels for the data were computed with the Curve Fitting toolbox in Matlab.

EXPERIMENT 2

To determine changes in turbulence with incremental medialization of the vibrating surface of the glottis only, we needed a special design. A new model was created without any medialization of the membranous or cartilaginous glottis for the right vocal fold. As the silicone was setting, a balsa-wood block (3 × 10 × 10 mm) was placed in the silicone corresponding to the paraglottic space. The silicone was allowed to set. A small aluminum plate was affixed to the lateral aspect of the block. A 12-mm hose clamp was placed around the model such that the height of the clamp aligned with the block. An 8/32 screw was inserted through the clamp so that the amount of medialization could be controlled with each turn of the screw (Fig 3). Each revolution of the screw resulted in 1.08 mm of medialization. Hot-wire measurements were then taken as previously described without medialization, followed by 0.54, 1.08, 1.62, and 2.16 mm of medialization. The widths of the glottal exit in the middle coronal plane and posterior coronal plane were 3.06 and 5.42 mm, respectively. The length of the glottal exit was 20.3 mm. Visual inspection confirmed that the subglottis was not medialized.

RESULTS

Velocity and length scales were normalized to account for differences in laryngeal anatomy. Length scales were normalized by dividing the distance of each measurement point from the origin (r) by the distance from the jet center to the point at which the mean velocity dropped to half of its value at the center velocity ($r_{1/2}$). The axial component of the mean velocity (U) was normalized by the maximum velocity (U_{max}). This normalization has been described elsewhere.[13]

For experiment 1, models were created for 4 laryngeal specimens before and after medialization of the subglottis. Each model was tested, making a total of 8 cases. For each case, measurements were taken in the anterior, middle, and posterior planes. For experiment 2, measurements were made for the case of no medialization, followed by 0.54, 1.08, 1.62, and 2.16 mm of medialization of the glottis only. There was no subglottal medialization for any of the 5 cases in experiment 2.

EXPERIMENT 1

Figure 4 demonstrates the best-fit curves of mean velocity (Fig 4A,C,E) and TI (Fig 4B,D,F) for the presurgery and postsurgery models. Confidence intervals (95%) are designated by hashed lines. The baseline profile, representing airflow at the inferior edge of the subglottis, is also displayed on each graph for comparison (solid black curve).

Anterior Plane. Figure 4A,B represents the mean and TI best-fit curves for the anterior plane. The velocity profiles of the models before and after subglottal medialization generally resembled the baseline profile in the anterior plane. The average maximum TI in the shear layer decreased from 11.4% before medialization to 9.0% after medialization (Fig 5). These values were both slightly less than the baseline value (11.7%).

Middle Plane. Figure 4C,D represents the best-fit

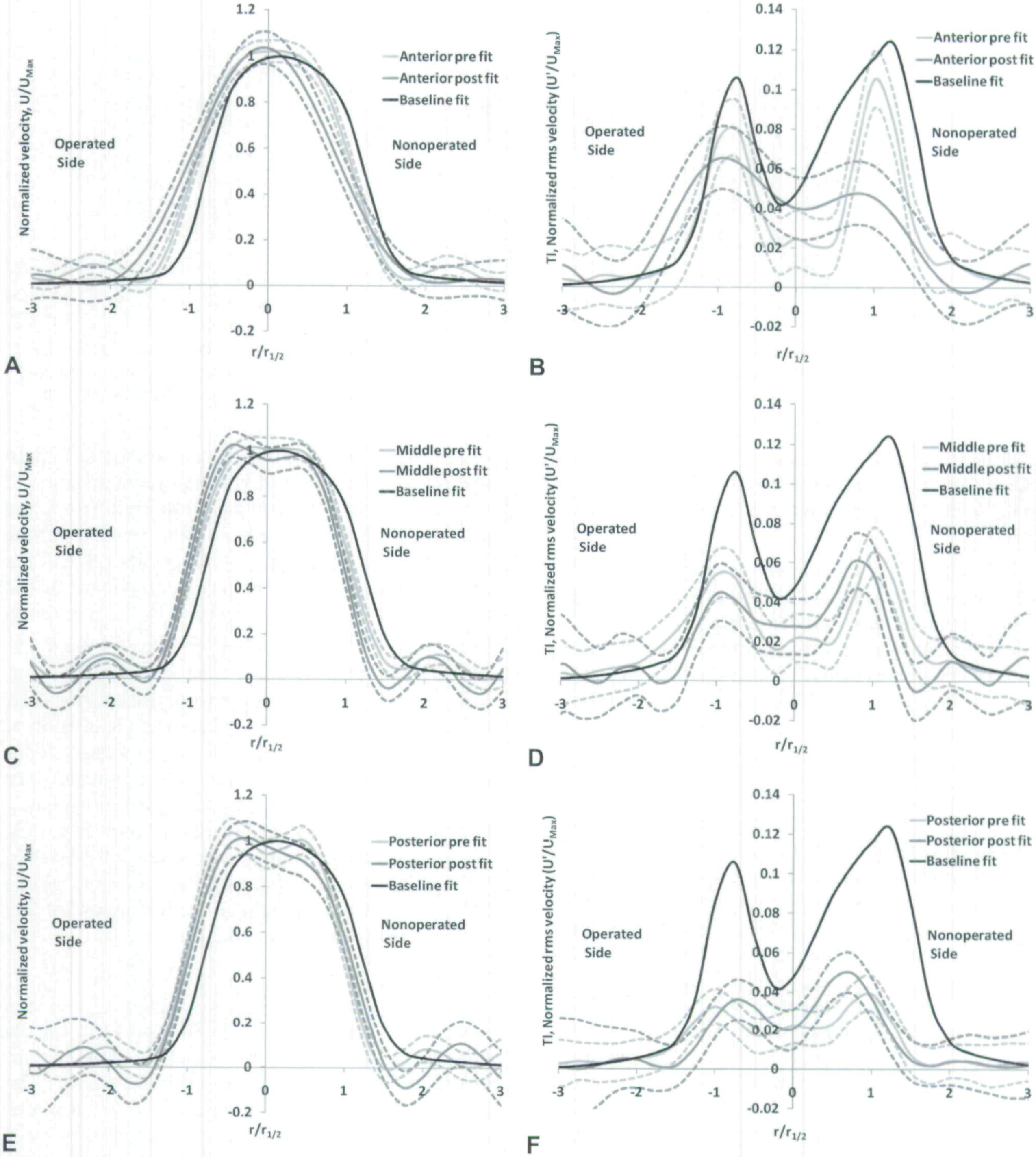

Fig 4. Velocity and turbulence intensity (TI) profiles. Best-fit curves are indicated by solid lines. Hashed lines represent 95% confidence interval for each curve. **A)** Velocity profile in anterior coronal plane. **B)** Turbulence profile in anterior coronal plane. **C)** Velocity profile in middle coronal plane. **D)** Turbulence profile in middle coronal plane. **E)** Velocity profile in posterior coronal plane. **F)** Turbulence profile in posterior coronal plane. TI — normalized rms velocity (U'/U_{max}); U' — rms velocity; U_{max} — maximum velocity.

curves for the middle plane. Again, the velocity profiles of the models before and after subglottal medialization resembled the baseline profile. The average maximum TI in the shear layer increased from 6.2% to 7.3% (Fig 5). Both the before and after values were less than the baseline (11.7%).

Posterior Plane. Figure 4E,F corresponds to the posterior plane. The velocity profiles again resembled the baseline profile. The average maximum TI in the shear layer decreased only slightly, from 5.0% before to 4.6% after (Fig 5). These values were significantly less than the baseline value of 11.7%.

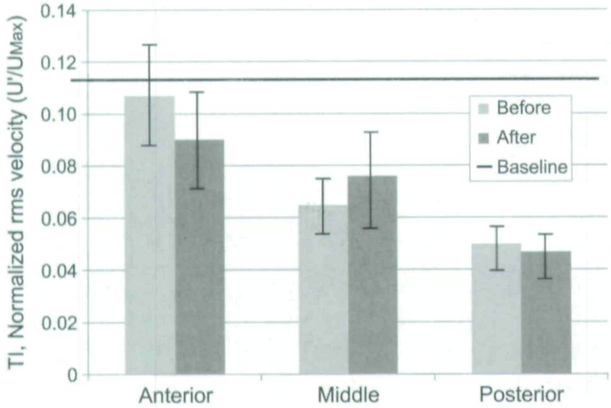

Fig 5. Average maximum TI (shear layer) for anterior, middle, and posterior coronal planes in experiment 1 (presence of subglottal medialization).

EXPERIMENT 2

Figure 6 displays the results of the incremental medialization (expressed in terms of the percentage of glottal area that was medialized) for 1 model in the middle and posterior planes. In the middle plane (Fig 6A), it is clear that the average maximum TI increased with increasing medialization, although the change is not significant for medialization up to 35%. Moving from 35% to 53% medialization, the TI dramatically increased (from 12% to 30%), even though the glottal gap decreased. In the posterior plane, the TI likewise increased with increasing medialization (7.6% to 11%).

DISCUSSION

The purpose of the current study was to demonstrate how changes in subglottal shape affect the TI of airflow entering the glottis. Previous literature has already shown that the smooth, converging shape of the conus elasticus acts to reduce the TI.[13] This turbulence reduction has clinical significance, since increased levels of turbulence can lead to a decreased HNR and increased breathiness.[10,11] Patients with UVFP typically suffer from a breathy voice and a decreased HNR.[19]

For experiment 1, the TI was reduced even when the subglottis was fully medialized and the smoothly converging shape was disrupted. However, visual inspection found that medialization of the subglottis actually produced medialization of the trachea also, resulting in a fairly smooth transition at the subglottal-tracheal border. This finding was seen for all 4 cases and for many canine larynges in our other work.

On the other hand, in experiment 2, the sharpness of the angle between the superior edge of the subglottis and the inferior edge of the vocal fold depended on the amount of medialization. The transition was fairly smooth up to 35% medialization. However, at 53% medialization, the transition was seen to be very sharp (ie, a very noticeable ledge was introduced). Similar findings have been qualitatively noted in our work with excised human and canine larynges.

As opposed to experiment 1, all of the medialization cases in experiment 2 resulted in a glottal gap; the smallest gap was seen in the case of 53% medialization. For experiment 2, the largest ARR is also seen in the case of 53% medialization. As described in the Introduction, the TI usually decreases as the ARR increases. This would suggest that the TI should be lowest for the case of 53% medialization; however, the exact opposite finding was noted. Our findings are most likely due to the fact that the transition between the subglottis and glottis was much smoother for medialization up to 35% than for medialization of 53%. As described previously, both the ARR and the smoothness of the transition are important for turbulence reduction. In experiment 2, it was noted that the effects of a sharp transition negate any turbulence reduction caused by area reduction; these findings are consistent with observations in fluid mechanics.

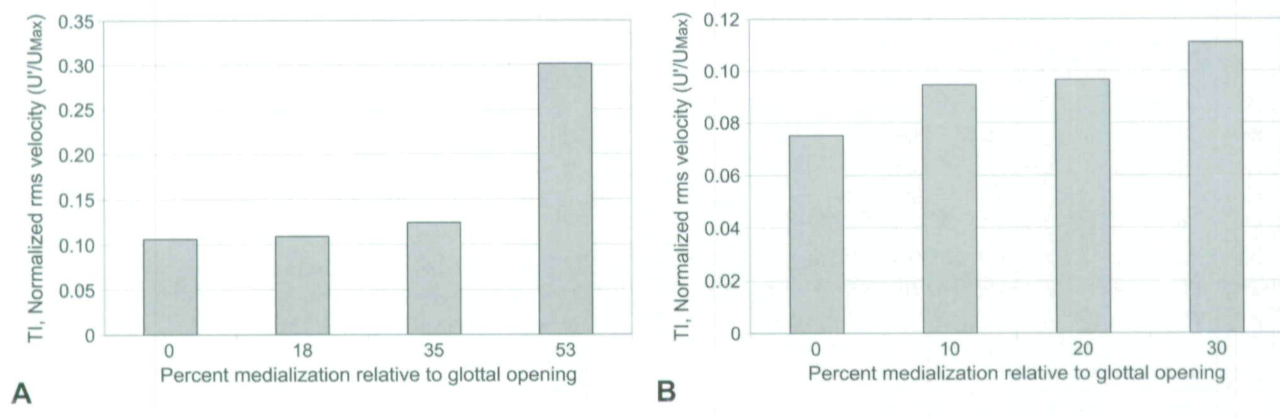

Fig 6. Average maximum TI for incremental medialization in **A)** middle shear layer and **B)** posterior shear layer (experiment 2). Amount of medialization is expressed as percentage of area of original glottal opening that is medialized.

The findings of experiment 2 suggest that large amounts of medialization of the glottis only will introduce high amounts of turbulence even if the glottal gap is closed. For smaller amounts of medialization, it may not matter whether the subglottis is medialized. Experiment 1 suggests that complete medialization of the subglottis does not introduce much turbulence. Our qualitative inspection of the silicone models and excised canine larynges showed that the transition is much smoother if the "ledge" is at the tracheal-subglottal level than if it is at the subglottal-glottal level. Thus, this study suggests that the subglottis should be medialized, especially in the case of larger glottal gaps.

However, there are several limitations of this study. First, silicone models were used to replicate a biological system. As noted previously, these disadvantages are weighed against benefits that come with using models.[22] We are planning on repeating these experiments on excised canine and human larynges. Additionally, in the current study we only investigated one substance (carved silicone block) for medializing the fold. Future research should investigate how different substances (Gore-Tex, Radiesse, etc) differentially alter airflow patterns. Future studies should also directly investigate how changes in the ARR before and after medialization thyroplasty affect laryngeal airflow patterns.

CONCLUSIONS

Medialization thyroplasty is a well-accepted phonosurgical procedure for improving voice quality in patients with UVFP. Changes in the subglottal shape after medialization thyroplasty can alter the turbulence of airflow entering the glottis. Although it changes the shape of the subglottis, complete medialization of the subglottis does not seem to affect the turbulence reduction effect of the subglottis. On the other hand, medialization of the glottis can introduce significant amounts of turbulence if the amount of medialization is large. The findings of this study suggest that the subglottis should be medialized in medialization thyroplasty. However, this study needs to be repeated on excised larynges.

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