Contribution of Undesired Medial Surface Shape to Suboptimal Voice Outcome After Medialization Laryngoplasty

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Summary: Objectives. Voice production in pathological conditions or after surgical intervention often involves undesired medial surface shape such as reduced vertical thickness and/or left-right asymmetry in medial surface shape. The effect of such undesired medial surface on voice production remains unclear, and is often not taken into consideration during planning of surgical intervention, due to difficulty of imaging the medial surface in patients. This study aims to better understand how voice outcomes are impacted by undesired medial surface shape.

Methods. Computational simulations were conducted to parametrically manipulate medial surface shape and stiffness and observe its consequence on voice production.

Results. The results showed that undesired medial surface shape can result in incomplete glottal closure, weak voice production, increased phonation threshold, and significantly reduced vocal efficiency, particularly in the presence of left-right stiffness asymmetry.

Conclusions. In addition to approximating the vocal folds, medialization laryngoplasty should aim to sufficiently increase medial surface thickness, which may improve voice outcomes in patients whose voices remain unsatisfactory or suboptimal after initial intervention. While a divergent implant may increase medial surface thickness, precise implant placement in anticipation of tissue and implant deformation during the insertion process is equally important in order to achieve desired medial surface shape and optimal voice outcomes.

Key Words: Medialization laryngoplasty—Medial surface shape—Vocal fold thickness—Left-right asymmetry—Voice outcome.

INTRODUCTION

Currently medialization laryngoplasty is often performed to improve voice production in the treatment of glottal insufficiency due to paralysis, paresis, or presbyphonia. While this procedure is generally effective in improving voice in most patients, voice quality does not always return to the extent desired. Some patients, particularly professional voice users, have reported dissatisfaction with the final result, despite the appearance of effective medialization at both the anterior and posterior glottis on endoscopic examination.[1-6] While an unsatisfactory or suboptimal outcome indicates unsuccessful restoration of vocal fold geometry, stiffness, and position back to their normal state in these patients, due to for example improper implant design or insertion, the specific underlying biomechanical causes of an unsatisfactory outcome are often unclear. As a result, it also remains unclear what surgical manipulations might further improve the voice in these patients.

In addition to the overall health condition of the patient, the degree of vocal fold approximation (or initial glottal gap) and vocal fold stiffness are two important factors in determining the glottal fluid-structure-acoustics interaction and the resulting voice quality, as discussed extensively in the voice literature,[7-9] and are often directly targeted during clinical interventions. In contrast, the effect of medial surface shape has received much less attention, due in part to the difficulty of directly visualizing the medial surface in humans. In the clinic, endoscopic examination often focuses on the glottal closure pattern and vocal fold adductory position in a two-dimensional plane as viewed from above, in which the medial surface shape in the vertical dimension is largely hidden during phonation. As a result, changes in medial surface shape, whether due to pathology or surgical intervention, are seldom taken into consideration during clinical intervention planning, despite the importance of medial surface shape to voice production and control as reported in many previous studies.[10-20] In particular, changes in medial surface vertical thickness has been shown to play an important role in regulating the glottal closure pattern and resulting voice quality.[10,11-13.]

In humans, vocal fold adduction in normal subjects would not only approximate the vocal folds, but also introduce subtle changes in medial surface shape (Figure 1). In particular, activation of the thyroarytenoid muscle has been shown to cause medial bulging of the inferior medial surface, which increases medial surface vertical thickness. When glottal insufficiency occurs due to vocal fold paralysis, paresis, or atrophy, medialization surgery may provide sufficient vocal fold approximation, but may not necessarily reproduce these subtle changes in medial surface shapes if the medial surface is not specifically targeted during intervention. Thus, voice production in pathology or after

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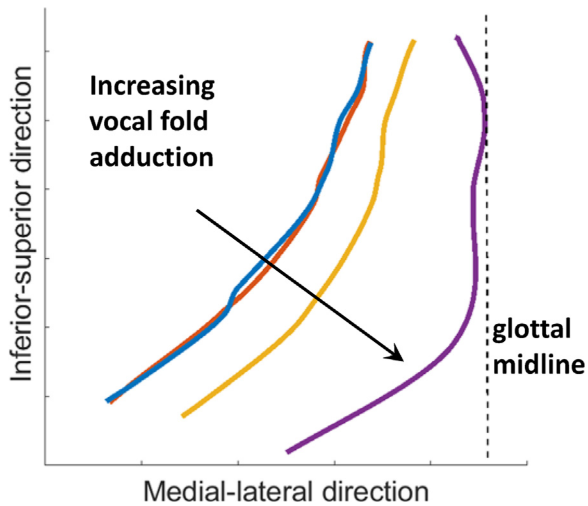

FIGURE 1. Vocal fold medial surface contour in the coronal plane at different levels of vocal fold adduction. Vocal fold adduction not only medializes the vocal folds but also introduces subtle changes in medial surface shape.

clinical intervention may involve undesired medial surface shape such as reduced vertical thickness and/or left-right asymmetry in medial surface shape, in addition to left-right asymmetry in stiffness. While the effect of left-right asymmetry in stiffness has been investigated in many previous studies,[21-26] no previous studies investigated the effect of left-right asymmetry in medial surface shape, or its interaction with stiffness asymmetry, on voice production.

The goal of this study was thus to evaluate to what extent voice production is affected by undesired medial surface shape (ie, small vertical thickness and/or left-right asymmetry in thickness, as observed in patients of vocal fold paralysis and after surgical intervention) and its interaction with left-right stiffness asymmetry. Due to difficulties of isolating changes in medial surface shape from other parameters in animal or human models, we used a computational model of the vocal folds to parametrically manipulate left-right asymmetry in medial surface shape and stiffness and observe its effect on voice production.

Our hypothesis was that undesired medial surface shape weakens the vocal folds' ability to achieve sufficient glottal closure during phonation, particularly in the presence of left-right stiffness asymmetry, and thus produces unsatisfactory or suboptimal voice outcomes even if the vocal folds are sufficiently medialized at rest. For this purpose, while the initial glottal gap plays an important role in determining the voice outcome, in this study we focused on conditions in which the vocal folds were sufficiently approximated, as often the case after medialization surgery. With a better understanding of how interaction between asymmetry in medial surface shape and asymmetry in stiffness affects voice production in sufficiently medialized vocal folds, we hoped to provide some insights into why the voice outcome in some patients remains unsatisfactory or suboptimal after surgical intervention and what can be done to further improve the voice outcome.

METHODS

The three-dimensional vocal fold model developed in our previous studies[13-15] was used in this study. The reader is referred to these previous studies for details of the model formulation. This model was able to reproduce experimental observations, particularly in left-right asymmetric conditions.[26] Each vocal fold was modeled as a two-layer, transversely isotropic linear material with a plane of isotropy perpendicular to the anterior-posterior (AP) direction, with the body layer representing the thyroarytenoid muscle and the cover layer representing the lamina propria and epithelium. A sketch of the vocal fold model is shown in Figure 2. Each vocal fold is geometrically parameterized by five control parameters, including the vocal fold medial surface vertical thickness T, vocal fold length L, body- and cover-layer depths D_b and D_c, and initial glottal angle α which controls the degree of vocal fold approximation. The material control parameters for each vocal fold layer include the transverse Young's modulus E_t, AP Young's modulus E_{ap}, AP shear modulus G_{ap}, and density.

In this study, we considered unilateral paralysis/paresis in the right vocal fold, which reduced its ability to modulate either the medial surface shape or vocal fold stiffness. This was modeled in this study by a reduced vertical thickness $T = 1$ mm and reduced cover-layer stiffness $G_{apc} = 1$ kPa on the right vocal fold, in contrast to $T = 3$ mm and $G_{apc} = 20$ kPa on the neuromuscularly intact left vocal fold. These values were chosen based on previous experimental and computational studies.[16,27-32] It should be noted that while in this study we only varied the AP stiffness, vocal fold paralysis/paresis likely impacts vocal fold stiffness in both the longitudinal and transverse direction and in both layers, which will be addressed in a future study.

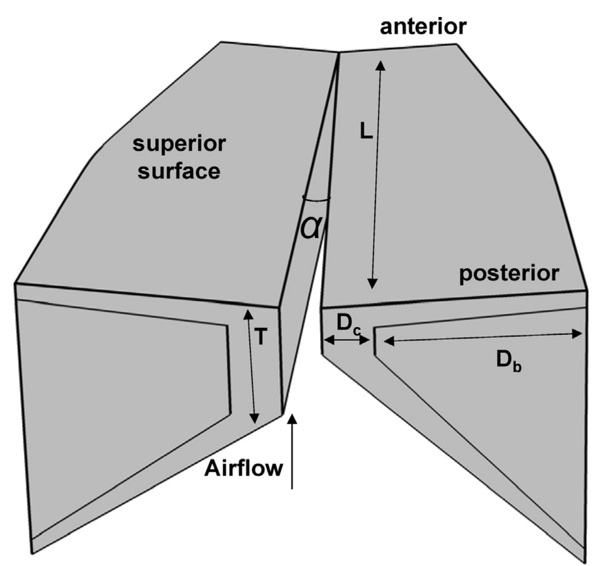

FIGURE 2. The three-dimensional vocal fold model and key geometric control parameters. In this study, left-right asymmetry in medial surface shape was modeled by varying the vertical thickness of the medial surface T of the two vocal folds.

TABLE 1.
Vocal Fold Left-Right Asymmetry Type (asymmetry in thickness only, asymmetry in stiffness only, and asymmetry in both), and Left/Right Thickness T and Stiffness G_{apc} Values for the Seven Vocal Fold Conditions Investigated in this Study

Left/Right	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Asymmetry	none	thickness	thickness	thickness	stiffness	stiffness	both
T (mm)	3/3	2/1	3/1	4.5/1	3/3	2/2	3/1
G_{apc} (kPa)	20/20	20/20	20/20	20/20	20/1	20/1	20/1

For all conditions E_t = 4kPa, and the initial glottal angle was 1.6°.

Specifically, seven typical cases of varying degrees of left-right asymmetry in the vertical thickness T and cover-layer AP stiffness G_{apc} were considered (Table 1). Case 1 was a left-right symmetric condition. Cases 2-4 modeled conditions with left-right asymmetry in thickness alone, whereas cases 5 and 6 modeled conditions with left-right asymmetry in stiffness alone, at different thickness values. Finally, case 7 modeled a condition with left-right asymmetry in both thickness and stiffness. As mentioned earlier, in order to focus on the effect of left-right asymmetry, the initial glottal angle was set to a small value of 1.6 degrees, which corresponded to a barely abducted glottal configuration with the lowest phonation threshold pressure,[14] simulating the effect of a successful medialization surgery. For all conditions, the vocal folds were connected to a vocal tract corresponding to the /ɑ/ sound.

For each of the seven conditions, voice simulation was performed for subglottal pressures ranging from 100 Pa to 1800 Pa, which covers the range in normal phonation and some pathological conditions.[33,34] For each subglottal pressure and vocal fold condition, a half-second of sustained /ɑ/ sound was simulated at a sampling rate of 44100 Hz.

Data analysis was performed using the last 0.25 seconds of each simulation to avoid transient effects. The phonation threshold pressure for each vocal fold condition was extracted as the minimum subglottal pressure producing sustained phonation. The A-weighted sound pressure level (SPL) was calculated from the output acoustics. The minimum glottal area was calculated from the glottal area waveform. From the glottal flow waveform, the closed quotient was calculated as the fraction of the cycle in which the glottal flow falls within the lower 10% between the minimum and maximum glottal flow rate. The maximum flow declination rate (MFDR) was calculated as the negative peak of the time derivative of the glottal flow waveform. The voice source spectrum was also calculated from the time derivative of the glottal flow waveform, from which H1-H2k and H1-H5k, measures of higher-order harmonic excitation, were calculated as the amplitude difference between the first harmonic and the harmonic nearest 2 kHz and 5 kHz, respectively.

RESULTS

Figure 3 shows the glottal flow waveform and voice source harmonic spectrum for the seven conditions, for a subglottal pressure of 1.2 kPa. Figure 4 compares the phonation threshold pressure and selected acoustic, aerodynamic, and vibratory measures across the seven vocal fold conditions. These measures were calculated also at a subglottal pressure of 1.2 kPa. This high subglottal pressure was chosen so that phonation was reached in all seven cases shown, thus allowing comparison across conditions. The general trend remained qualitatively the same at lower pressures.

Effect of left-right thickness asymmetry alone

For the symmetric condition (case 1), vocal fold vibration was able to completely shut off the glottal flow during each vibration cycle (Figure 3). The glottal flow waveform was asymmetric, with the opening phase longer than the closing phase and a rapid flow declination. This rapid flow declination led to a strong negative peak in the waveform of the time derivative of the glottal flow (large MFDR in Figure 4) and strong higher-order harmonic excitation in the 2-5 kHz range of the voice source spectrum (low values of H1-H2k and H1-H5k in Figure 4). This strong harmonic excitation is important to producing voice with a bright voice quality. The mean glottal flow was about 150 mL/s, which is within the range of loud voice production in normal subjects.[33]

When the ability to modulate vocal fold thickness is lost or weakened, the affected vocal fold often has a small thickness. This was modeled in the three asymmetric conditions (cases 2-4) in Figure 3. All three conditions had a small vertical thickness T = 1 mm on the right vocal fold, whereas the thickness of the left vocal fold was gradually increased (Table 1), simulating contralateral thickness compensation. Figure 3 shows that except for case 4 with maximum contralateral thickness compensation (T = 4.5mm/1mm), complete glottal closure was not achieved for the other two asymmetric conditions (cases 2 and 3), and the glottal flow waveform was much less asymmetric, with a much reduced MFDR (Figure 4). Cases 2 and 3 also had much weaker higher-order harmonic excitation (large H1-H2k and H1-H5k). The produced voice was weak in quality. Compared to the symmetric condition in case 1, both cases 2 and 3 had a much higher phonation threshold pressure, and were vocally much less efficient, producing a much lower SPL but consuming a higher mean glottal flow, which is undesired for conserving respiratory effort.[35]

Figures 3 and 4 also show that this negative effect of thin vocal fold can be partially compensated by

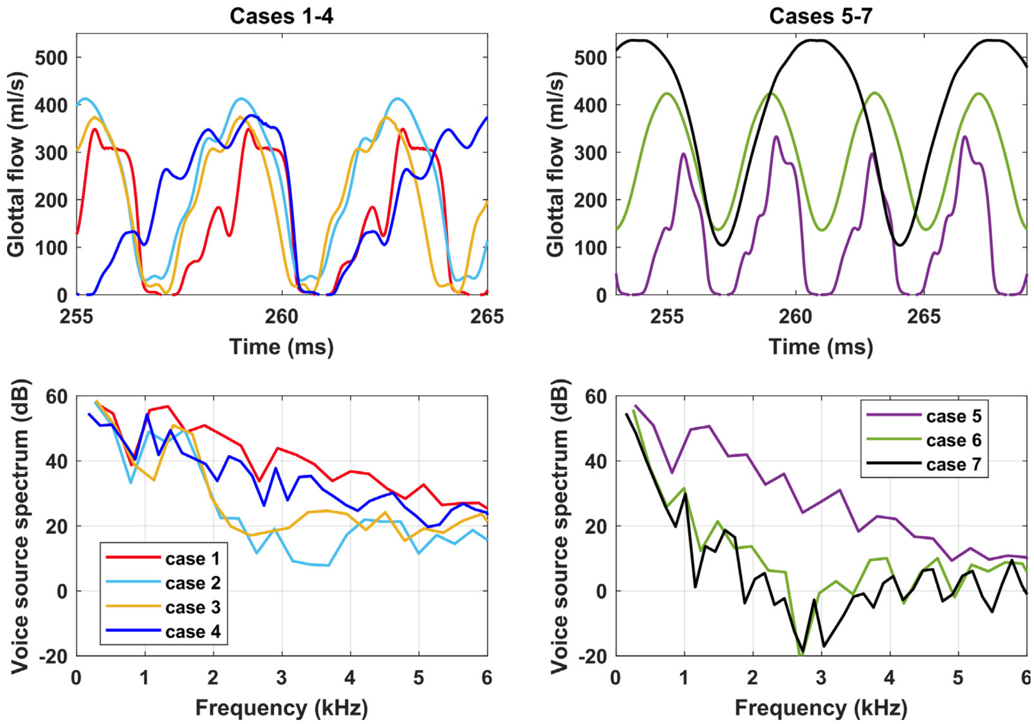

FIGURE 3. The glottal flow waveform (top) and voice source spectrum (bottom) for the seven vocal fold conditions. Case 1 is a symmetric condition. Cases 2-4 have left-right asymmetry in thickness only, whereas cases 5 and 6 have left-right asymmetry in stiffness only. Case 7 has left-right asymmetry in both thickness and stiffness.

significantly increasing the thickness of the contralateral fold (case 4; T = 4.5 mm). This allowed case 4 to produce a much higher SPL, although the mean glottal flow was still higher than normal. In our previous simulations,[12,15] vocal folds with a thickness of 4.5 mm in a left-right symmetric condition often produced voices with a pressed voice quality and exhibited irregular vocal fold vibration, reminiscent of conditions of vocal fold hyperadduction. Thus, while the negative effect of a reduced thickness in the affected vocal fold can be compensated by contralateral compensation, this likely requires significantly increased laryngeal muscle effort.

Increasing thickness mitigated the negative impact of left-right stiffness asymmetry

Cases 5 and 6 were conditions with left-right asymmetry in stiffness only, at different thickness values. When the vocal folds were sufficiently thick (case 5), the vocal folds with left-right stiffness asymmetry were still able to completely shut off the glottal flow, although the MFDR was smaller compared to the symmetric condition in case 1 (Figure 4). This small effect of left-right stiffness asymmetry under conditions of small initial glottal angles is consistent with the observations in previous studies.[21,22,24] However, voice production was more severely degraded in vocal folds that were not sufficiently thick, as in case 6. The phonation threshold pressure was 1.4 kPa, the highest among all seven conditions. The vocal folds vibrated with a large minimum glottal opening, resulting in high airflow consumption, a much reduced MFDR, and weak higher-order harmonic excitation.

The differences between cases 5 and 6 suggest that the negative impact of stiffness asymmetry on the produced voice can be mitigated by increasing vocal fold thickness, either through increased vocal fold adduction or surgical manipulations, as discussed further below. With sufficient thickening in both folds, case 5 was able to almost match the output SPL and airflow consumption in the symmetric condition in case 1, although the higher-order harmonic excitation was still weaker. It is worth noting that these improvements were obtained even in the presence of large left-right stiffness asymmetry, which is otherwise difficult to correct during surgical intervention.

Presence of both stiffness and thickness asymmetry significantly degraded the produced voice quality

When both asymmetries in stiffness and thickness were present (case 7), the vocal folds were no longer able to sufficiently close the glottis during vibration, resulting in a considerably high minimal glottal flow (about 100 mL/s) throughout the entire oscillation cycle. The glottal flow waveform was almost sinusoidal, with significantly reduced higher-order harmonics in the voice source spectrum (Figure 4). The phonation threshold pressure was also considerably higher in case 7 (around 1 kPa). Voice production was the least efficient in case 7, producing a SPL of 64 dB while using a mean glottal flow of 376 mL/s. In other words, phonation under this condition would require high vocal

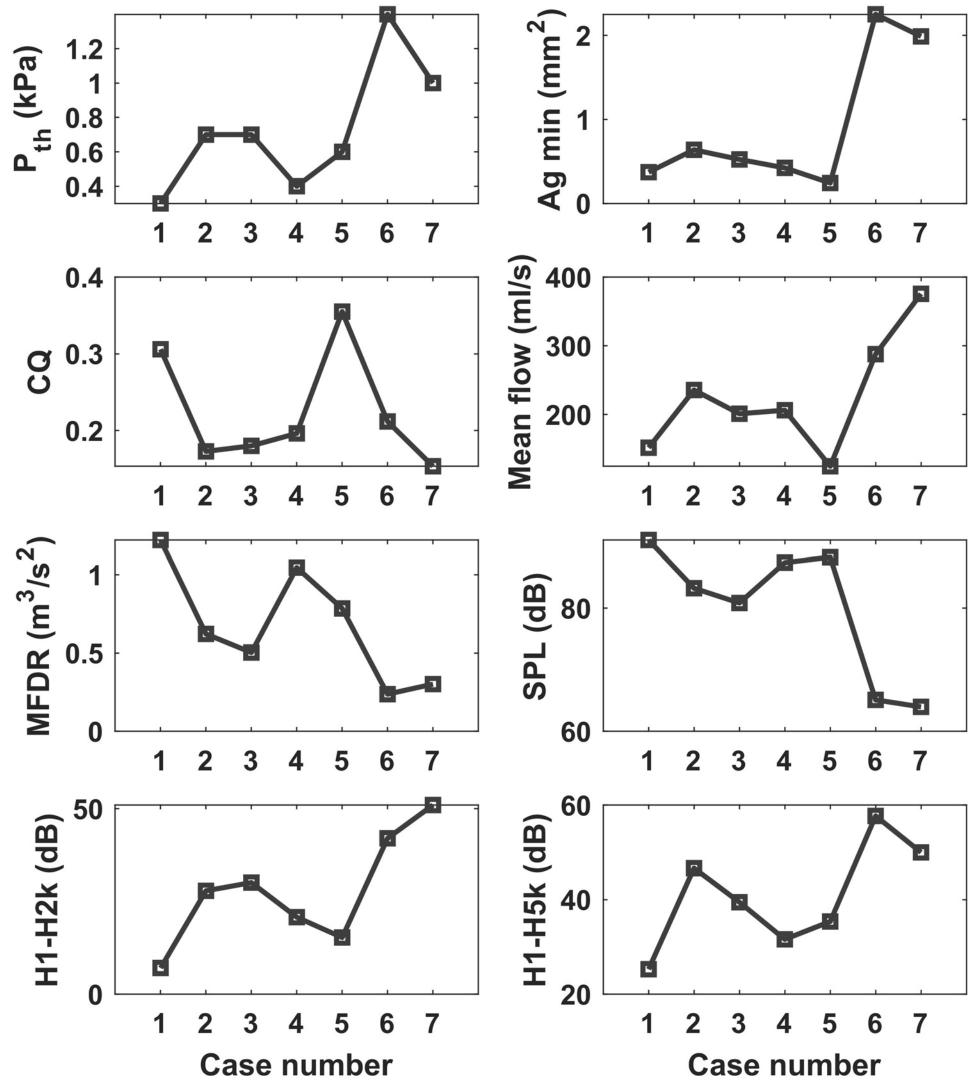

FIGURE 4. Selected measures of voice production for the seven vocal fold conditions for a subglottal pressure of 1.2 kPa. Case 1 is a symmetric condition. Cases 2-4 have left-right asymmetry in thickness only, whereas cases 5 and 6 have left-right asymmetry in stiffness only. Case 7 has left-right asymmetry in both thickness and stiffness.

effort and still may not be able to produce sufficiently high vocal intensity or strong higher-order harmonics.

DISCUSSION AND CONCLUSIONS

The goal of this study was to investigate to what extent voice production is negatively impacted by undesired medial surface shape. Our results showed that very thin vocal folds or left-right asymmetry in medial surface thickness can result in increased phonation threshold pressure, incomplete glottal closure, and weak voice production with reduced higher-order harmonic excitation (Figure 3), despite sufficient vocal fold medialization at rest. This was particularly the case when left-right stiffness asymmetry was also present (case 7), as often occurs in vocal fold paralysis/paresis or after medialization surgery, in which case the vocal efficiency was significantly reduced whereas airflow consumption was significantly increased.

The results may provide some insights into why the voice outcome in some patients remains unsatisfactory or suboptimal despite the appearance of effective vocal fold medialization at rest on endoscopic examination, particularly for patients with unilateral vocal fold paralysis or paresis. For these patients, voice production almost always involves left-right stiffness asymmetry, both before and after medialization surgery. In the presence of left-right stiffness asymmetry, if the vocal folds are not sufficiently thick (case 6) or exhibit left-right thickness asymmetry (case 7; Figure 1), voice production would be very inefficient, consuming too much airflow, effortful, and the produced voice would be weak with few higher-order harmonics. This would be so even if the vocal folds were sufficiently approximated at rest from an endoscopic view.

Our results also showed that increasing medial surface thickness on the affected vocal fold and overall thickness on both folds can considerably mitigate the negative effect of left-right stiffness asymmetry (cases 4 and 5). Thus, in addition to other intervention goals (eg, medialization, arytenoid adduction, and stiffness goals), medialization surgery planning should also consider the impact of surgical intervention on the medial surface shape and aim to restore desired medial surface shape. Specifically, implant design and insertion should aim to increase medial surface thickness on the affected vocal fold in addition to medialization. This is consistent with previous observation that proper implant position in all three planes is required to produce acceptable voice outcomes.[2,32,36]

While such thickness increase can be achieved with implants with a divergent medial surface shape (ie, the medial-lateral dimension of the implant is larger at the inferior end than its superior end), precise implant placement in anticipation of tissue and implant deformation in the insertion process is equally important. For example, stiff implants such as Silastic often maintain their shape during the insertion process.[32] Thus, the post insertion medial surface shape can be effectively controlled by the pre insertion shape of stiff implants, provided sufficient precision in the implant insertion angle and depth can be achieved (a divergent, stiff implant placed slightly above the vocal fold level or directly upwards would have minimal impact on medial surface thickness). A stiff implant with a divergent medial surface shape may also increase the inferior stiffness of the medial surface, a condition that may facilitate glottal closure.[37]

On the other hand, soft implants with stiffness comparable to the vocal folds (but greater than 10 kPa in order to provide sufficient lateral support to the vocal folds against subglottal pressure[38]), and possibly GoreTex, tend to deform significantly during the insertion process.[32] Thus, control of post insertion medial surface shape and insertion depth are likely difficult and pre insertion implant shape likely would not matter as much in such implants. Soft implants also tend to stretch in the vertical direction when compressed in the medial-lateral direction during insertion, and may impact medial surface shape in a large vertical span. Thus, while soft implants may be more forgiving to imprecision in insertion angle, it is also difficult to precisely target a specific area (e.g., the inferior portion) of the medial surface. Further imaging studies such as the one by Zhang et al[32] would be required to better understand tissue and implant deformations in the implant insertion process. Finally, soft implants are less likely to result in large left-right stiffness asymmetry, and thus make it easy for contralateral stiffness compensation to potentially improve voice outcomes.

An important limitation of this study was the simplified vocal fold geometry and stiffness conditions used in the simulations. In particular, the medial surface shape in humans varies considerably along the anterior-posterior direction, which has been shown to significantly affect the glottal closure pattern and voice production.[39] While cause-effect relationships should remain qualitatively the same, understanding the role of the medial surface and its interaction with stiffness and glottal gap in realistic, clinically-relevant human phonation conditions is needed before translation to clinical applications. This is particularly important in order to determine the range of medial surface shape that should be targeted during surgical intervention, which is the focus of future studies.

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