A Methodology to Quantify the Effective Vertical Thickness of Prephonatory Vocal Fold Medial Surface

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Summary: Objective. The shape of the vocal fold medial surface, particularly its vertical thickness, has been shown in computational and physical modeling studies to be highly influential in regulating glottal closure during phonation. However, because of the difficulty to quantify the vertical thickness in real vocal folds, this influence has often been overlooked in clinical contexts. Therefore, the goal of this study is to present a method to calculate an effective vertical thickness of the medial surface that is predictive of the glottal closure pattern during phonation.

Methods. An effective vertical thickness of the medial surface is calculated as a weighted integral of the medial surface contour along the vertical dimension. The weight is one for the part of the medial surface within a fixed threshold distance from the most medial point, and decays exponentially otherwise. The influence of the threshold distance value on the effective thickness value is investigated. Additionally, the sensitivity of the calculated effective thickness to slight misidentification of the vertical glottal midline is also studied. The methodology is validated on the vocal fold medial surface data from a canine hemilarynx at different levels of thyroarytenoid muscle activation.

Results. For most threshold distances, the thickness follows an expected sigmoid-like trend with respect to the thyroarytenoid muscle activation level. A threshold distance of 0.05 mm appears optimal as it produced thickness changes in a range comparable to previous computational and experimental studies. The methodology is relatively robust to slight misidentification of the vertical glottal midline.

Conclusions. A methodology to estimate the effective vocal fold vertical thickness from medial surface contours is proposed. The methodology can be applied in future studies to correlate medial surface shape to relevant parameters characterizing vocal fold vibration as well as clinical evaluation of treatment effectiveness.

Key Words: Medial surface–Vertical thickness–Computed tomography–Magnetic resonance imaging–Closed quotient.

INTRODUCTION

During phonation, the airflow coming from the lungs primarily interacts with the medial surface of the vocal folds. Therefore, the prephonatory shape of the medial surface is essential in controlling the vibration patterns of the vocal folds, which in turn affects the produced voice sound.[1-3] However, the variations of the prephonatory medial surface shape, particularly of the vertical thickness, and their influence on the vibration patterns, are often difficult to observe and quantify *in vivo*. Most previous studies have used numerical[4-9] or physical[10-12] models to investigate this influence, because those models allow for a clear definition and parameterization of the prephonatory vertical thickness of the vocal folds. Some of those studies revealed that increasing prephonatory vertical thickness increases the closure duration within one cycle (closed quotient).[4,12,13] In addition, one study by Zhang et al[14] demonstrated an improvement in glottal closure during phonation of excised human larynges, when the vocal folds were qualitatively made thicker. The increase in closure duration is likely due to the larger phase delay between the lower and upper margins of the medial surface associated with an increase in vertical thickness: when the glottis starts opening at the lower margin, the upper margin will continue to stay closed for a longer time for thicker folds.[4] Increasing the vertical thickness can also help counteract the effect of aerodynamic forces pushing the vocal folds apart, in the case of an increase in subglottal pressure. In a clinical context, where the goal is to improve the glottal closure pattern and closed quotient, treatment should therefore not only optimize the glottal gap in the horizontal dimension, but also the medial surface thickness in the vertical dimension.[4,15]

One of the main issues that prevents clinicians from considering the vertical thickness in treatment options, is the difficulty in quantifying the prephonatory vertical thickness in real vocal folds: because the real medial surface varies smoothly, the upper and lower margins are often not well-defined,[16,17] in contrast with the vocal folds in computational or physical models. Nevertheless, several studies proposed different methods to provide a geometric measure of the vocal fold thickness from x-ray and magnetic resonance images of the larynx. Notably, Hollien et al[18,19] estimated the vocal fold thickness from x-ray images of the larynx during phonation at different fundamental frequencies, by dividing the cross-sectional area of the vocal folds by their medial-lateral extent. They found values

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ranging from about 4.5 mm to about 9.5 mm for men and from 3 mm to 7 mm for women, where the thickness monotonically decreased when increasing the fundamental frequency of phonation. Another method employed by Hampala et al[20] defined thickness as the vertical extent of the medial surface falling within a threshold medial-lateral distance of the most medial point of the vocal folds. They measured thickness values ranging from approximately 3 mm to 5 mm when using a threshold distance of 1 mm, and from 4 mm to 6.4 mm when using a threshold distance of 2 mm. In addition, Tayama et al[21] used histologic sections of the vocal folds to define the thickness as the distance from the lower bound of the thyroarytenoid (TA) muscle to the upper limit of the vocal fold surface, and found values ranging from about 8.75 to 10.25 mm.

Alternatively, the vocal fold thickness can be defined as an "effective" thickness of the prephonatory medial surface, where its value is directly related to the glottal closure pattern during phonation. This definition was employed by Wu et al,[13] who used the same method as in the study by Hampala et al[20] but found that a much smaller threshold distance (0.05 mm) was needed to get a linear relationship between the prephonatory thickness value and the closed quotient. The measurement of such an effective thickness could be applied to computed tomography scans or magnetic resonance images of the vocal folds in the coronal plane to predict glottal closure patterns in living human subjects. This may be used in clinical contexts to evaluate the necessity of increasing or decreasing the effective thickness to reach an optimal closure pattern,[15] and to evaluate treatment outcomes.

The goal of this study is therefore to propose a methodology to measure the effective thickness of the prephonatory medial surface based on the method used in Hampala et al[20] and Wu et al.[13] Two measurement parameters are investigated to understand their influence on the measurement. The first parameter is the value of the threshold distance, which can impact the average and range of the measured thickness. The other parameter is the rotation of the vertical glottal midline in the coronal plane, simulating potential misidentification of the vertical midline. The vertical glottal midline can be difficult to accurately identify in computed tomography scans or magnetic resonance images, particularly when there is a gap between the vocal folds, and a misidentification can potentially have an impact on the measurement of the effective thickness. The investigation of this parameter aims at estimating the magnitude of this impact.

To validate the methodology, it is applied to three-dimensional (3D) reconstructed prephonatory medial surface contour data from a canine hemilarynx, where the TA muscle was stimulated at 13 different activation levels of increasing magnitude, from 0 (no activation) to 12 (maximum activation). The prephonatory effective thickness at different levels of TA activation is analyzed for different values of the threshold distances and glottal midline rotation. The contraction of the TA muscle is known to have the largest effect on vocal fold thickness,[16,17,22-25] and the closed quotient was previously shown to be correlated with the level of TA activation.[26,27] Based on the known effect of the TA muscle activation and on previous results from computational and physical modeling studies, the following criteria are used to determine an optimal value for the threshold distance, ordered by level of importance:

(1) The prephonatory effective thickness should increase monotonically with increasing TA activity, following a trend similar to a sigmoid function: barely increase until a certain TA activation level, then increase more rapidly before reaching a plateau for higher TA activation levels.[26]
(2) The range of the prephonatory effective thickness should be similar to the ranges used in other computational or physical modeling studies[6,12,13] (the thickness values used in those studies are listed in Table 1).
(3) The average value of the prephonatory effective thickness should be similar to the average values used in other computational or physical modeling studies[6,12,13] (the thickness values used in those studies are listed in Table 1).

TABLE 1.
Range of the Medial Surface Prephonatory Thickness Values Used in Previous Computational and Experimental Studies

Study	Medial surface thickness range
Zhang, 2016[6]	1-4.5 mm
Wu et al, 2019[13]	0.2-6 mm
Taylor et al, 2022[12]	1.01-6.01 mm

METHODS

Vocal fold vertical thickness measurement

The medial surface contour is expressed in a (x, y) plane, where x is the medial-lateral axis (x increases toward the medial direction) and y is the vertical (inferior-superior) axis. The vertical glottal midline corresponds to $x = 0$, and the medial surface contour is defined as $x_c(y)$. The most medial point on the surface is located and its position on the x axis is defined as x_m. Then, the horizontal distance from the most medial point d_m is defined as $d_m(y) = x_m - x_c(y)$. The first attempts to measure the thickness by simply calculating the vertical extent of the surface that falls within the threshold distance (as described in [20]) occasionally revealed discontinuities in the thickness values from one slice to another, due to the medial surface contours sometimes containing both convex and concave portions. Consequently, the original method was altered to smooth out those discontinuities, by measuring the thickness T as a weighted integral along the vertical dimension of the medial surface

$$T = \int_L^U w(d_m)\,dy, \tag{1}$$

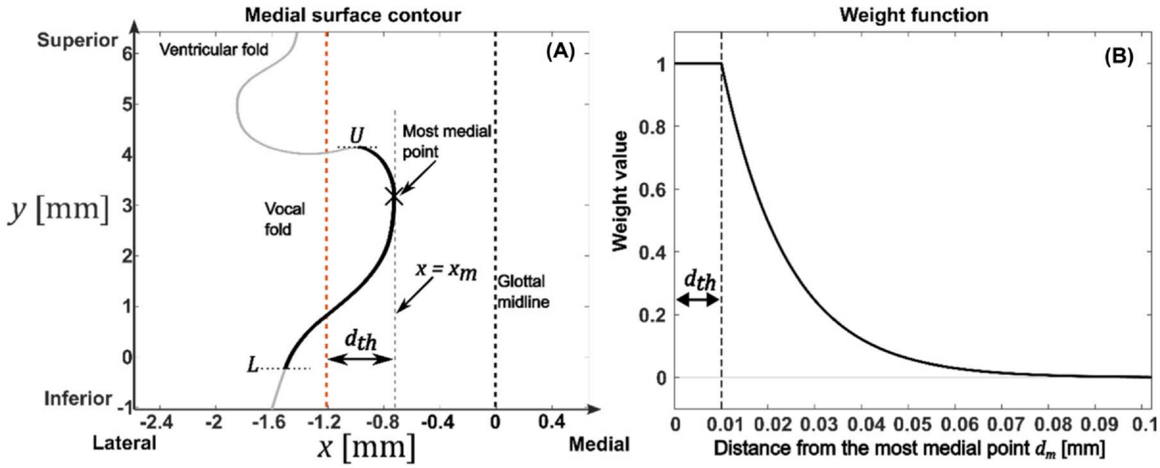

FIGURE 1. Description of the method to measure the vertical thickness. **A.** Medial surface at one coronal position where the plain gray line represents a typical contour as observed in computed tomography scans and the plain black line (between lower limt L and upper limit U) shows the portion of the contour used for thickness measurement. **B.** Weight function used in the integral to calculate the vertical thickness.

where U and L are the upper (superior) and lower (inferior) limits of the vocal fold medial surface (see Figure 1A), and $w(d_m)$ is the weight function. The weight is defined at each vertical location according to the horizontal distance from the most medial point $d_m(y)$ and the threshold distance d_{th}

$$w(d_m) = \begin{cases} 1, & \text{if } d_m(y) \le d_{th} \\ e^{-\alpha(d_m(y)-d_{th})}, & \text{if } d_m(y) > d_{th} \end{cases} \quad (2)$$

where α is a factor determining how fast the weight function decreases. In this study, α is set to 70, which allows smoothing out the thickness discontinuities without substantially altering the average thickness value. The weight function is plotted in Figure 1B for $d_{th} = 0.01$ mm. The precise locations of U and L are not so critical because the weight function decays very fast. Nevertheless, the upper limit of the medial surface U should not be beyond the highest (most superior) location on the medial surface, as shown in Figure 1A. It is also worth noting that the glottal gap (ie, x_m) has no effect on the calculated thickness. Thus, while the glottal gap and medial surface shape often covary in humans, our method allows us to isolate thickness changes from changes in the glottal gap.

Experimental setup and protocol

The data presented in this study stem from *in vivo* canine experiments performed in previous studies, and therefore the detailed description of the experimental setup and procedure can be found, for example, in.[28-30] It is briefly described here for clarity.

One mongrel canine was put under general anesthesia, and the larynx was prepared into a hemilarynx to expose the left vocal fold. The vocal fold medial surface was marked with black India ink to form a grid of flesh points. A prism was placed along the glottal midline, which allowed to record a stereoscopic view of the vocal fold medial surface and to reconstruct it in 3D using the software DaVis. A digital high-speed camera was used to register the motion of the vocal fold medial surface at 3000 frames per second and with a resolution of 384-by-672 pixels. Spatial dimensions were calibrated using a plate with a known pattern.

The TA muscle was stimulated with an electric current pulse train across 13 linearly spaced levels of pulse amplitude, from no activation (level 0) to a maximum activation level, defined as the level beyond which no further change in the medial shape was observed (level 12).

Data analysis

For each TA activation level, the medial surface contour was extracted by DaVis with a 0.043-mm resolution in both the anterior-posterior and inferior-superior axes. The contour was extracted at 275 coronal slices along the anterior-posterior axis, each containing 399 vertical points. Data were processed and analyzed in MATLAB 2019b (The MathWorks, Inc., Natick, MA). The vocal fold surface is divided into three equal-length parts along the anterior-posterior axis, and the average value of the thickness in the middle third is calculated.

Investigated parameters

The thickness is calculated using seven different values of the threshold distance d_{th}: 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, and 1 mm, spanning the range used in previous studies. In addition, to simulate potential misidentification of the vertical glottal midline, the medial surface is rotated in the coronal plane (about the anterior-posterior axis) by angles from $-10°$ to $10°$ with increments of $1°$, resulting in a total of 21 tilting conditions. The range of $-10°$ to $10°$ is chosen similarly to the study by Schlegel et al.[31] The rotation is applied to the left vocal fold as oriented in Figure 1A. Thus, a negative angle corresponds here to a clockwise rotation, causing the medial surface to become more convergent (ie, larger convergence angle between the two medial surfaces), and a positive angle corresponds to a counterclockwise rotation, causing the medial surface to become more divergent, with respect to the vertical glottal midline.

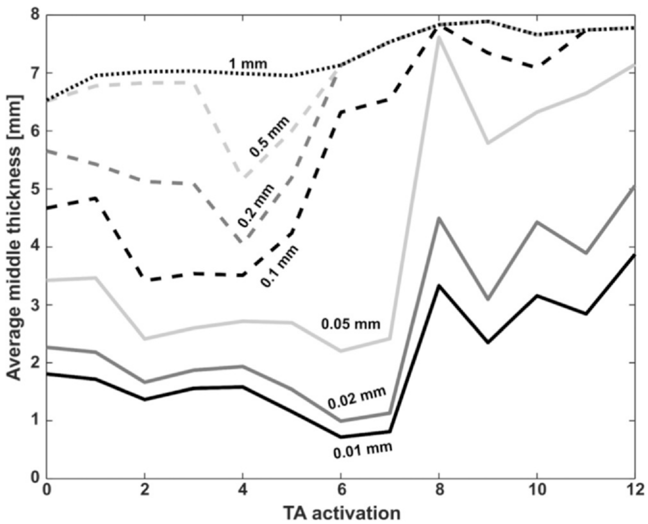

FIGURE 2. Average thickness in the middle portion of the vocal fold, calculated for each TA activation level and for different values of the threshold distance $\mathbf{d_{th}}$ (indicated next to each line).

RESULTS

Influence of threshold distance

Figure 2 depicts the values of the average thickness in the middle portion of the vocal fold, for each TA activation level and for each threshold distance value. Additionally, Table 2 provides the numerical values of the range (difference between the maximum and minimum values) and average of the thickness values across all activation levels. As expected, the measured thickness consistently increases when increasing the threshold distance.

For lower threshold values (0.01 to 0.05 mm), the trends in the thickness values with increasing TA activation levels are very similar, but the range of the thickness increases with increasing threshold values and is the largest for d_{th} = 0.05 mm (Table 2). As the value of d_{th} increases further above 0.05 mm, the range of thickness values progressively decreases.

TABLE 2.
Range of Thickness Values (Difference Between the Maximum and Minimum Value) and Average Value Across All Activation Levels, for Each Threshold Distance Value

Threshold distance (mm)	Average value of the thickness across all activation levels (mm)	Range of thickness values across all activation levels (mm)
0.01	2.0	3.2
0.02	2.7	4.1
0.05	4.3	5.4
0.1	5.8	4.4
0.2	6.5	3.8
0.5	7.1	2.7
1	7.3	1.4

For higher values of d_{th} (0.2 to 1 mm), the calculated thickness values stay constant for TA activation levels from 6 to 12. This can be explained by the fact that, at those levels of activation, the anterior and middle parts of the vocal fold are pressed against the glass plate, which replaces the glottal midline in the hemilarynx experiment. In this case, the entire reconstructed medial surface is confined to a small medial-lateral slice, with the medial-lateral extent of the slice even smaller than the threshold distance d_{th}, and therefore the value of the thickness corresponds to the entire vertical extent of the surface. For d_{th} = 1 mm, this is the case at all activation levels because the medial-lateral extent of the extracted medial surface in our dataset has a maximum of approximately 1 mm.

Influence of the medial surface rotation

As previously mentioned, precise identification of the vertical glottal midline is difficult, particularly when there is a gap between the two vocal folds. In our dataset, a large part of the medial surface is pressed against the glass plate for TA activation levels 6 to 12, which means that at those levels of activation, the vertical glottal midline is much easier to correctly identify. Consequently, the rotation of the medial surface is only applied here to the conditions where there is a glottal gap, that is, at TA activation levels 0 to 5, for which the vertical glottal midline is more likely to be misidentified.

The variations of the thickness values with medial surface rotation are shown in Figure 3. The rotation generally decreases the measured thickness. This effect is, however, stronger for negative angle rotations, which make the medial surface more convergent with respect to the vertical glottal midline. Additionally, negative angle rotations have some effect on the trend of the effective thickness, as its value increases at muscle activation levels 2 and 3 more than other levels, especially for a rotation of − 4° (see Figure 3).

To investigate the deviations of the thickness due to misidentification of the vertical glottal midline, we calculated the average value and the range (difference between the maximum and minimum value) of the thickness across all TA activation levels, for each threshold distance and rotation angle. Figure 4 presents those values of the average (Figure 4A) and the range (Figure 4B) as a percentage of the "reference" value at 0° rotation.

The analysis of the average effective thickness confirms that its value decreases with rotation in most cases, with a visibly stronger effect for clockwise rotations (negative angles). The only exceptions are for a − 1° rotation with d_{th} = 0.01 mm to d_{th} = 0.05 mm, and for counterclockwise rotations (positive angles) up to 7° with d_{th} = 0.5 mm. The dashed lines in Figure 4A indicate the range of rotation angles within which the average thickness is between 80% (underestimation) and 120% (overestimation) of the reference value at 0°. For negative angles, the limit is − 4° for threshold distances up to 0.02 mm, and gradually increases to reach − 10° at threshold distances ≥0.5 mm. For positive

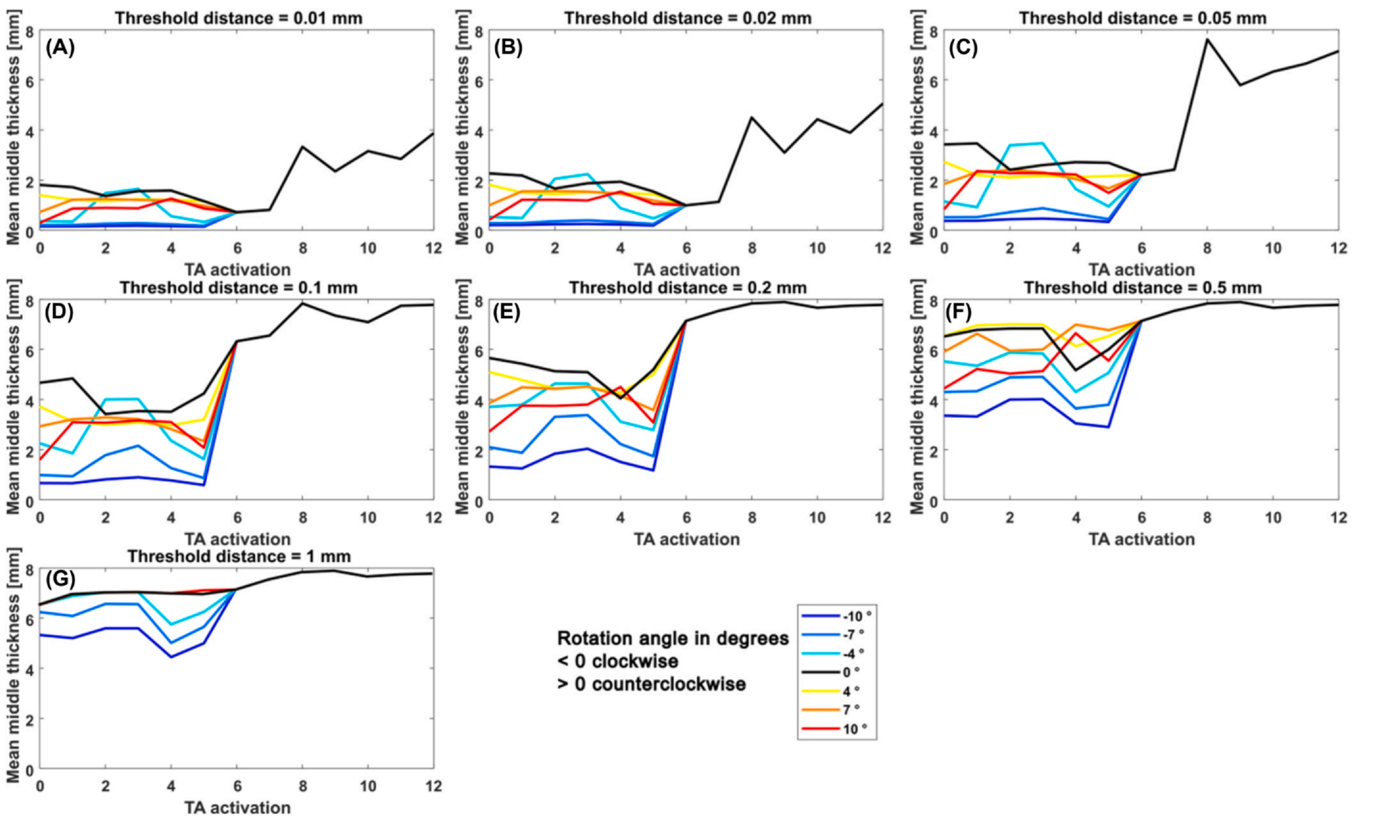

FIGURE 3. Vertical thickness measured at the middle portion of the vocal fold for each TA activation level, showing the effect of medial surface rotation from − 10° (clockwise—the glottis becomes more convergent) to + 10° (counterclockwise—the glottis becomes more divergent). Only some of the angles are shown for clarity. The values are shown for each threshold distance: (**A**) 0.01 mm, (**B**) 0.02 mm, (**C**) 0.05 mm, (**D**) 0.1 mm, (**E**) 0.2 mm, (**F**) 0.5 mm, and (**G**) 1 mm. For each panel, the thickness at 0° (reference value) is displayed in black.

angles, the limit consistently stays at 10° for all threshold distances.

Regarding the range of thickness, the limit is ± 10° for threshold distances up to 0.02 mm, as visible in Figure 4B. It suddenly decreases for higher threshold distances and oscillates between − 2° and − 3° for negative angles. For positive rotation angles, the limit is higher at 9°, 5°, 8°, 9°, and 10° at d_{th} = 0.05 mm, d_{th} = 0.1 mm, d_{th} = 0.2 mm, d_{th} = 0.5 mm, and d_{th} = 1 mm, respectively.

DISCUSSION

The goals of this study are to explore a methodology to quantify the vocal fold medial surface vertical thickness and apply this methodology to 3D-reconstructed medial surface data from a hemilarynx. Particularly, the intention is to investigate how different parameters impact the measured thickness and to determine an optimal value for the threshold distance.

Regarding the trends of the measured effective thickness, most threshold distances result in a meaningful trend, where the thickness increases with increasing TA activation. Except for d_{th} = 0.2 mm and d_{th} = 0.5 mm, the thickness follows a trend similar to a sigmoid function: it stays rather constant for lower TA activation, then suddenly increases around an activation level of 6, 7, or 8 (recall Figure 2), and reaches a plateau for higher TA activation levels. In this regard, most threshold distances (except 0.2 and 0.5 mm) appear appropriate to estimate the effective thickness, based on criterion (1).

The largest threshold distance (1 mm) displays, however, a reduced range of the measured thickness (only 1.4-mm range, with values from 6.5 mm to 7.9 mm), suggesting that this threshold distance is not useful to estimate the effective thickness in a meaningful way, following criterion (2). Smaller threshold distances appear to exhibit a more meaningful range of thickness values (> 3 mm). Particularly, a threshold distance of 0.05 mm results in the maximum range of 5.4 mm, which is very close to the range of thickness found by Wu et al[13] (5.8 mm) using the same threshold distance. Smaller threshold distances of 0.01 mm or 0.02 mm result in a smaller range of thickness (3.2 mm and 4.1 mm), which is comparable with the range of thickness used in the computational model by Zhang.[4,6] Nevertheless, because the study by Wu et al[13] is based on data from magnetic resonance images of the vocal folds, a threshold value of 0.05 mm appears more appropriate.

In general, the prephonatory effective thickness consistently increases with increasing threshold distance (see Figure 2), which is an expected feature of this methodology, due to the rounded shape of the medial surface of the vocal folds. This feature is also visible in the analysis of

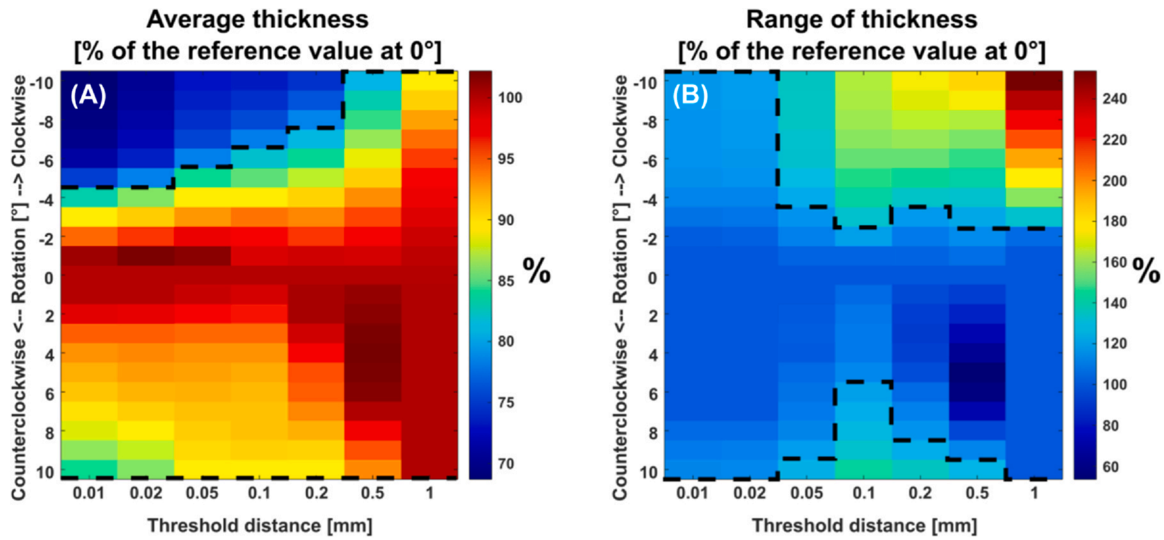

FIGURE 4. Variations of the average value (**A**) and range (**B**) of the thickness across all TA activation levels. Those variations are shown for each threshold distance (columns) and rotation (rows) condition. For each panel, the values of the range and of the average are indicated as a percentage of the "reference" value at 0° rotation. The dashed black lines indicate the range of rotations within which the average value and range of the effective thickness are between 80% and 120% of the reference value.

the average value of the effective thickness for each threshold distance (Table 2). It shows that threshold distance values above 0.05 mm exhibit average thickness values that are much higher than the values found in previous computational (as in [4,6]) and physical (as in [12]) studies that have a straight, vertical medial surface with clearly defined upper and lower margins, or used data from MRI scans with a threshold distance of 0.05 mm.[13] Consequently, the results further support the relevance of using lower threshold values (0.01 to 0.05 mm) for the effective thickness, based on criterion (3).

While this optimal threshold value of 0.05 mm may seem small when compared with the overall dimensions of the vocal folds, which are in the order of 10 mm,[21,32] it is consistent with the fact that changes in medial surface shape due to laryngeal posturing are often subtle. Thus, if too large a threshold value is used, the calculated thickness will largely reflect shape changes on the inferior surface and be less sensitive to subtle changes on the medial surface. For example, Hampala et al[20] calculated vocal fold thickness using a 1-mm and 2-mm threshold distance, and only revealed very small variations of the vocal fold thickness.

The second parameter investigated in this study is the rotation of the medial surface, simulating potential misidentification of the vertical glottal midline. In images from computed tomography or magnetic resonance imaging, the vertical glottal midline can sometimes be difficult to correctly identify, particularly when there exists a gap between the vocal folds. This can potentially have a substantial effect on the measurement of the effective thickness, and the investigation of this parameter serves to assess the sensitivity of our methodology to misidentification of the vertical glottal midline. The results suggest that the methodology is generally more sensitive to clockwise rotation (negative angles, causing the medial surface of the left vocal fold to be more convergent or less divergent) than counterclockwise rotation (positive angles, causing the medial surface of the left vocal fold to be less convergent), as visible in Figures 3 and 4. For threshold distances up to 0.05 mm, a maximum clockwise rotation of − 3° appears to be a reasonable limit to avoid significant variations in the trend of the effective thickness at lower TA activation levels, while a counterclockwise rotation up to 9° causes less than a 20% deviation in both the average and range of the effective thickness value (Figure 4). This suggests that, when one is unsure about the exact location of the vertical glottal midline in coronal images, it is better to err on the side of a less-convergent medial surface in order to obtain a more accurate estimation of the effective thickness.

This study has two main limitations. The first limitation is the fact that only one larynx was used to validate the methodology. The extent to which the range and average value of the effective thickness could vary between different larynges is unknown, even though Wu et al[13] found rather similar thickness values for the two larynges they used. Additionally, inherent differences between male and female human larynges[19,33] can also result in substantial differences in the range and average values of the effective thickness. More work is needed to better understand how those differences may impact the proposed methodology. The second limitation is the lack of closed quotient measurement. The data from this study stem from static experiments where the vocal fold was not phonated, therefore the closed quotient could not be measured. The methodology should be further validated using computed tomography scans or magnetic resonance images when the closed quotient data are also available.

CONCLUSION

This study provides the basis for a methodology to measure the "effective" vocal fold medial surface vertical thickness that can be used to predict the glottal closure pattern during phonation. The influences of the threshold distance and of potential misidentification of the vertical glottal midline on the trends of change, range, and average values of the measured thickness with varying TA stimulation are examined. An optimal threshold value is determined to be 0.05 mm, as it results in a trend, range, and average value of the thickness closest to the ones reported in previous computational and experimental studies. The methodology appears relatively robust to slight misidentification of the vertical glottal midline (− 3° to 10°), particularly when such misidentification leads to a less-convergent medial surface contour, which still provides an adequate estimation of the effective thickness. This suggests that in case of uncertainty about the exact location of the vertical glottal midline in coronal images, erring on the side of a less-convergent medial surface is better to obtain a more accurate estimation of the effective thickness. The methodology can be used in a clinical context to evaluate treatment outcomes in the case of nonoptimal glottal closure patterns, such as hypoadduction or hyperadduction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Zhang Z. Mechanics of human voice production and control. *J Acoust Soc Am.* 2016;140:2614–2635. https://doi.org/10.1121/1.4964509.
2. Berry DA, Montequin DW, Tayama N. High-speed digital imaging of the medial surface of the vocal folds. *J Acoust Soc Am.* 2001;110:2539–2547. https://doi.org/10.1121/1.1408947.
3. Titze IR. The physics of small-amplitude oscillation of the vocal folds. *J Acoust Soc Am.* 1988;83:1536–1552.
4. Zhang Z. Vocal fold vertical thickness in human voice production and control: a review. Published online March 22 *J Voice.* 2023. https://doi.org/10.1016/j.jvoice.2023.02.021.
5. Zhang Z. Laryngeal strategies to minimize vocal fold contact pressure and their effect on voice production. *J Acoust Soc Am.* 2020;148:1039–1050. https://doi.org/10.1121/10.0001796.
6. Zhang Z. Cause-effect relationship between vocal fold physiology and voice production in a three-dimensional phonation model. *J Acoust Soc Am.* 2016;139:1493–1507. https://doi.org/10.1121/1.4944754.
7. Li S, Scherer RC, Wan M. Effects of vertical glottal duct length on intraglottal pressures in the convergent glottis. *Appl Sci.* 2021;11:4535. https://doi.org/10.3390/app11104535.
8. Li S, Scherer RC, Fulcher LP, et al. Effects of vertical glottal duct length on intraglottal pressures and phonation threshold pressure in the uniform glottis. *J Voice.* 2018;32:8–22. https://doi.org/10.1016/j.jvoice.2017.04.002.
9. Chang S. *Computational fluid-structure interaction for vocal fold modeling* [doctoral dissertation]; 2016.
10. Scherer RC, Shinwari D, De Witt KJ, et al. Intraglottal pressure profiles for a symmetric and oblique glottis with a divergence angle of 10 degrees. *J Acoust Soc Am.* 2001;109:1616–1630.
11. Li S, Scherer RC, Wan M, et al. The effect of entrance radii on intraglottal pressure distributions in the divergent glottis. *J Acoust Soc Am.* 2012;131:1371–1377. https://doi.org/10.1121/1.3675948.
12. Taylor CJ, Thomson SL. Optimization of synthetic vocal fold models for glottal closure. *J Eng Sci Med Diagn Ther.* 2022;5:031106. https://doi.org/10.1115/1.4054194.
13. Wu L, Zhang Z. Voice production in a MRI-based subject-specific vocal fold model with parametrically controlled medial surface shape. *J Acoust Soc Am.* 2019;146:4190–4198. https://doi.org/10.1121/1.5134784.
14. Zhang Z, Chhetri DK. Effect of changes in medial surface shape on voice production in excised human larynges. *J Acoust Soc Am.* 2019;146:EL412–EL417. https://doi.org/10.1121/1.5131044.
15. Zhang Z. Contribution of undesired medial surface shape to suboptimal voice outcome after medialization laryngoplasty. *J Voice.* 2024;38:1220–1226. https://doi.org/10.1016/j.jvoice.2022.03.010.
16. Hirano M. Morphological structure of the vocal cord as a vibrator and its variations. *Folia Phoniatr Logop.* 1974;26:89–94. https://doi.org/10.1159/000263771.
17. Hirano M. Phonosurgery: basic and clinical investigations. *Otol Fukuoka.* 1975;21(suppl 1):239–440.
18. Hollien H. Vocal fold thickness and fundamental frequency of phonation. *J Speech Hear Res.* 1962;5:237–243.
19. Hollien H, Curtis JF. A laminagraphic study of vocal pitch. *J Speech Hear Res.* 1960;3:361–371. https://doi.org/10.1044/jshr.0304.361.
20. Hampala V, Laukkanen AM, Guzman MA, et al. Vocal fold adjustment caused by phonation into a tube: a double-case study using computed tomography. *J Voice.* 2015;29:733–742. https://doi.org/10.1016/j.jvoice.2014.10.022.
21. Tayama N, Kaga K, Chan RW, et al. Functional definitions of vocal fold geometry for laryngeal biomechanical modeling. *Ann Otol Rhinol Laryngol.* 2002;111:83–92. https://doi.org/10.1177/000348940211100114.
22. Vahabzadeh-Hagh AM, Zhang Z, Chhetri DK. Quantitative evaluation of the in vivo vocal fold medial surface shape. *J Voice.* 2017;31:513.e15–513.e23. https://doi.org/10.1016/j.jvoice.2016.12.004.
23. Choi HS, Ye M, Berke GS, et al. Function of the thyroarytenoid muscle in a canine laryngeal model. *Ann Otol Rhinol Laryngol.* 1993;102:769–776. https://doi.org/10.1177/000348949310201006.
24. Van den Berg J. Register problems. *Ann N Y Acad Sci.* 1968;155:129–134. https://doi.org/10.1111/j.1749-6632.1968.tb56756.x.
25. Wu L, Zhang Z. A parametric vocal fold model based on magnetic resonance imaging. *J Acoust Soc Am.* 2016;140:EL159–EL165. https://doi.org/10.1121/1.4959599.
26. Luegmair G, Chhetri DK, Zhang Z. The role of thyroarytenoid muscles in regulating glottal closure in an in vivo canine larynx model . *Proc Meet Acoust.* 2014;22:060007. https://doi.org/10.1121/2.0001504.
27. Mendelsohn AH, Zhang Z, Luegmair G, et al. Preliminary study of the open quotient in an ex vivo perfused human larynx. *JAMA Otolaryngol Neck Surg.* 2015;141:751–756. https://doi.org/10.1001/jamaoto.2015.1249.
28. Chhetri DK, Neubauer J, Berry DA. Graded activation of the intrinsic laryngeal muscles for vocal fold posturing. *J Acoust Soc Am.* 2010;127:EL127–EL133. https://doi.org/10.1121/1.3310274.

29. Chhetri DK, Neubauer J, Bergeron JL, et al. Effects of asymmetric superior laryngeal nerve stimulation on glottic posture, acoustics, vibration. *Laryngoscope.* 2013;123:3110–3116. https://doi.org/10.1002/lary.24209.
30. Vahabzadeh-Hagh AM, Zhang Z, Chhetri DK. Three-dimensional posture changes of the vocal fold from paired intrinsic laryngeal muscles. *Laryngoscope.* 2017;127:656–664. https://doi.org/10.1002/lary.26145.
31. Schlegel P, Döllinger M, Reddy NK, et al. Validation and enhancement of a vocal fold medial surface 3D reconstruction approach for in-vivo application. *Sci Rep.* 2023;13:10705. https://doi.org/10.1038/s41598-023-36022-6.
32. Titze IR. *The Myoelastic Aerodynamic Theory of Phonation.* Iowa City, IA, USA: National Center for Voice and Speech; 2006.
33. Titze IR. Physiologic and acoustic differences between male and female voices. *J Acoust Soc Am.* 1989;85:1699–1707.