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Article *in* The Annals of otology, rhinology, and laryngology · June 2001

DOI: 10.1177/000348940111000514 · Source: PubMed

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CHARACTERIZATION OF THE MEDIAL SURFACE OF THE VOCAL FOLDS

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A method is developed for the quantification of the medial surface of the vocal folds in excised larynges. Lead molds were constructed from the glottal airway of a canine larynx for 3 distinct glottal configurations corresponding to "pressed" folds, just barely adducted folds, and 1-mm-abducted folds as measured between the vocal processes. With a high-resolution laser striping system, the 3-dimensional molds were digitally scanned. Low-order polynomials were fitted to the data, and goodness-of-fit statistics were reported. For all glottal configurations, a linear variation (flat surface) approximated the data with a coefficient of determination of 90%. This coefficient increased to roughly 95% when a quadratic variation (curvature) was included along the vertical dimension. If more than the top 5 mm or so of the folds was included (the portion usually corresponding to vibration), a cubic variation along the vertical dimension was necessary to explain a change in concavity at the conus elasticus. These findings suggest the utility of a model based on a convergence coefficient and a bulging coefficient. For all glottal configurations, the convergence coefficients and bulging coefficients can be computed. Because pre-phonatory conditions have a profound influence on vocal fold vibration and on the quality of phonation, such shaping parameters are highly significant. With the viability of this method substantiated, it is envisioned that future studies will characterize greater quantities of glottal shapes, including those of human vocal folds.

KEY WORDS — glottis, larynx, vocal fold.

INTRODUCTION

Initial conditions and boundary conditions have a profound impact on many nonlinear dynamic systems. In vocal fold vibration, which represents such a nonlinear system, a small change in the pre-phonatory shape of the medial surface of the vocal folds can mean the difference between chest-like, falsetto-like, and fry-like vibration patterns, or it can mean the difference between periodic and aperiodic oscillations.[1] For phonosurgeons, who alter the glottal geometry in reconstructive procedures, pre-phonatory vocal fold shape is increasingly understood as a critical variable. For example, measurement of the angle of glottal opening and precise positioning of the arytenoid cartilage are becoming more and more common in phonosurgery.[2-4]

Several simulation models of vocal fold vibration have been used to quantify the subtleties of vocal fold shape.[5-7] These models solve second-order partial differential equations to describe the resultant vibrations. In such models, the specification of initial conditions, or pre-phonatory shape, is essential in making a reasonable prediction of the oscillations. A series of normal mode studies on the vocal folds has shown that phonation frequency has a remarkable correspondence with the lowest resonance frequency of the folds, as measured immediately before phonation.[8,9] Such resonance frequencies are known to be strongly influenced by glottal geometry.[10] However, to date, no quantitative data exist on these pre-phonatory shapes. In particular, previous magnetic resonance and computed tomographic images obtained from the vocal tract and laryngeal regions have not yielded the resolution needed for modeling the medial surface of the folds (on the order of 0.1 mm).

The focus of this report is the development of a method for high-precision quantification of the medial shape of the vocal folds in excised larynges. Once the methodological study is presented, future studies are envisioned in which greater numbers of molds will be analyzed, with more decisive conclusions drawn. The following questions will be probed. What order of polynomial must be used to approximate the vocal fold shape across a variety of glottal configurations? Does the theoretical model proposed by Titze,[11] which assumes a linear variation of vocal fold shape along the anterior-posterior length and a quadratic variation along the vertical depth, provide

From the Department of Speech Pathology and Audiology, National Center for Voice and Speech, The University of Iowa, Iowa City, Iowa. This work was supported by grant R29 DC03072 from the National Institutes of Health/National Institute on Deafness and Other Communication Disorders. This study was performed in accordance with the PHS Policy on Humane Care and Use of Laboratory Animals, the NIH *Guide for the Care and Use of Laboratory Animals*, and the Animal Welfare Act (7 U.S.C. et seq.); the animal use protocol was approved by the Institutional Animal Care and Use Committee (IACUC) of the University of Iowa (October 22, 1993).

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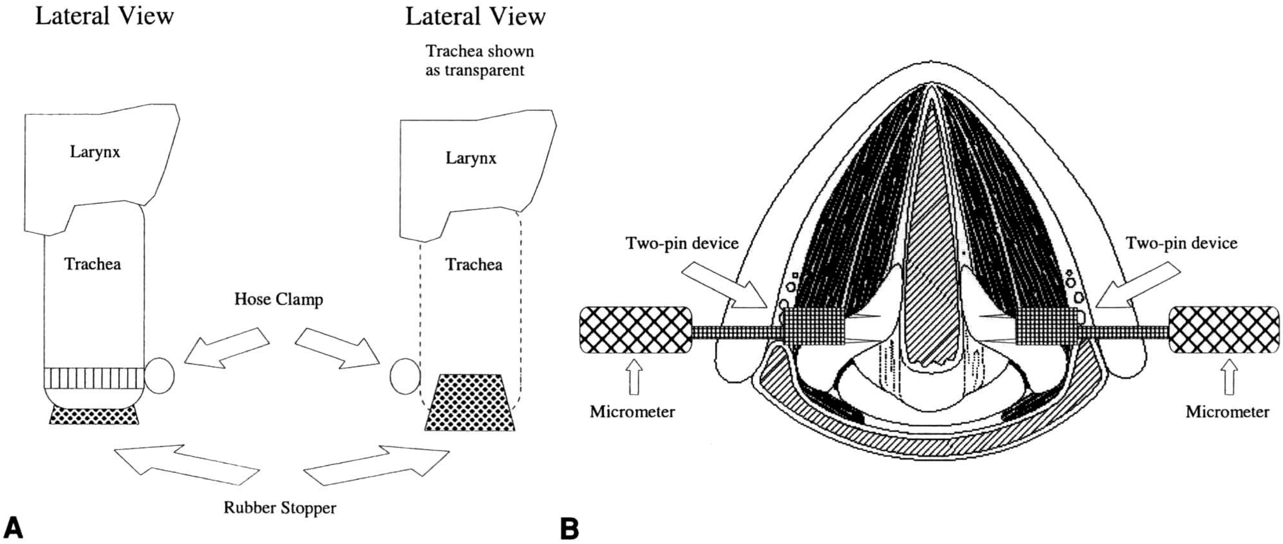


Fig 1. Views of larynx. **A)** Lateral view depicts stopper that was placed at base of trachea to prevent wax leakage during molding process. **B)** Superior view depicts 2-pin micrometer device used to control arytenoid adduction.

an adequate description of the molds? If so, what are the convergence coefficients and bulging coefficients of each of the molds, and how do these constants change as a function of glottal adduction?

METHODS

A canine larynx was obtained postmortem from an experimental animal weighing approximately 20 kg. Before molding the airway, we dissected the excised larynx to remove the epiglottis, the ventricular folds, and all but a short section (0.5 to 1 inch) of the trachea. The interior of the larynx was coated with a silicone gel to allow easy removal of the mold. A stopper, held in place with a hose clamp, was used to block the trachea (Fig 1A). The larynx was then mounted in a vertical orientation, and the vocal folds were adducted with 2-pin micrometer devices, as shown in Fig 1B. Once a desired level of adduction was achieved, molten wax (Tissueprep histologic wax) was injected into the glottal airway and left to harden.

In order to make a more permanent mold of the airway, we removed the wax mold and placed it in dental plaster so that the tracheal end of the wax mold broke the surface of the plaster (so that the wax could be removed later). After the plaster hardened, the wax was removed by placing the plaster-wax compound into a kiln and slowly heating the kiln to at least 327.5°C, which is the melting point of lead. The wax was burned away and was replaced with liquid lead. The lead mold was allowed to cool for 1 hour. Subsequently, the plaster was cracked away, leaving a 3-dimensional (3-D) lead mold of the glottal and subglottal airway, as well as a 3-D representation of the medial surface of the vocal folds. The molds appeared to yield a good representation of the glottal airway. There was no evidence of tissue deformation during the wax injection, or during hardening of the plaster or the reverse lead mold.

Three molds were obtained from the larynx, each mold corresponding to a unique glottal configuration: 1) an open larynx (a glottal width of approximately 1 mm, with no micrometer-adduction devices applied); 2) the arytenoids just barely adducted; and 3) the arytenoids pressed to the point of 1 mm beyond "just touching." Measurements of glottal width were taken between the anterior points of the vocal processes.

In preparation for analysis of the molds, it was necessary to digitize the surfaces. The physical orientation used throughout this report is as follows: z direction, the vertical dimension; y direction, the anterior-posterior length; and x direction, the medial-lateral dimension of the folds. The metallic composition of the lead molds facilitated digitization with a 3-D laser striping system. In particular, we used the IMAGINE2 laser striper, built by the Department of Artificial Intelligence at the University of Edinburgh, to digitize the molds.[12,13] The system measured the x coordinate with an error of approximately 0.1 mm, and scanned the surfaces in increments of 0.5 mm in the y and z directions. Scans were taken of all of the molds from 3 different orientations: the left, the top, and the right, as shown in Fig 2. Because the molds appeared to be predominantly symmetric, symmetry was assumed, and only the left view was analyzed. However, if one desired to analyze the geometric asymmetries between the left and right folds, the present technique could accommodate such a study (ie, both left and right views could be analyzed).

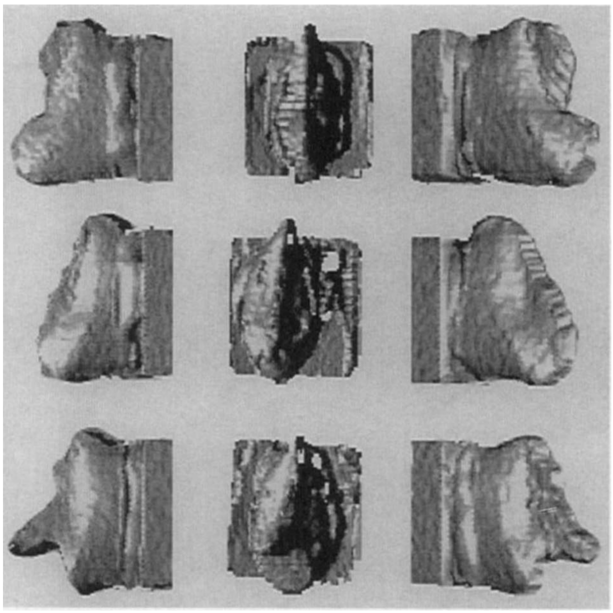


Fig 2. Surface rendering of 3-dimensional (3-D) data obtained with laser striper for larynx 1. Left, superior, and right views are shown from left to right in pictures, respectively. From top to bottom, open larynx, arytenoids just touching, and pressed arytenoid configurations are shown.

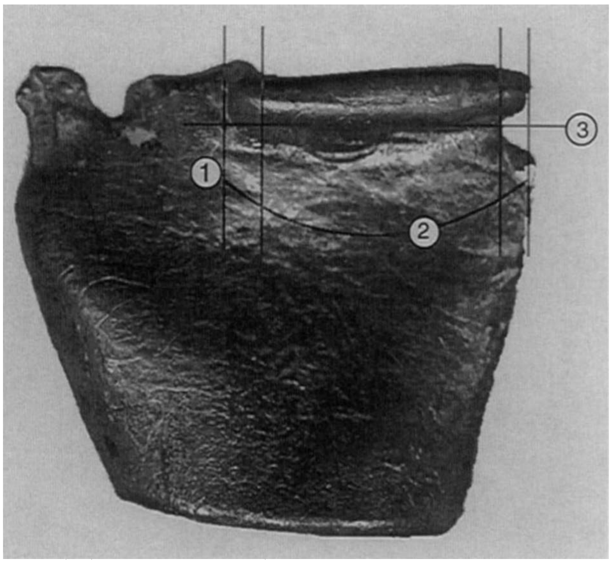


Fig 3. Side view of sample lead mold of glottal airway. Line 3 indicates superior edge of vocal fold, 2 indicates inferior edge on which tissue vibration is possible, and 1 indicates plausible choices for anterior-posterior boundaries. Although most extreme markers give more accurate indication of true vocal fold length, more interior markers were often used in this investigation in order to avoid noisy data near end points.

In modeling the medial surface of the folds, it was of particular interest to know which regions of the molds corresponded to vibrating tissues. Indeed, the focus of this investigation was the pre-phonatory shape of tissue regions in which oscillations might occur. Such data directly impact our computer models of vocal fold vibration and are also of interest in phonosurgery. Although the non-oscillating tissue regions were not the focus of this study, they could be useful for modeling subglottal airflow.

The region in which tissue vibration was possible is depicted on the lead mold shown in Fig 3, which illustrates a medial view of the mold. The numeral 3 delineates the superior surface of the folds, which appears as a clear indentation on the mold. Above this line, the molding material spilled over the top of the glottal airway. The numeral 2 marks the inferior boundary of vibrating tissue. Palpation of the subglottal wall on the original larynx (ie, not the mold) revealed that the depth to which tissue vibration could occur varied along the length of the folds. The depth was smaller at the anterior and posterior extremities than midway along the length. The inferior boundary was roughly symmetric about the midpoint of the membranous fold, curving upward anteriorly and posteriorly, as shown in Fig 3. The maximal depth of the region of vibration was approximately 5.6 mm on this mold.

The 4 vertical lines marked with a numeral 1 show 2 possible choices for the anterior and posterior boundaries of the vocal fold. Presumably, the most extreme positions give the most accurate estimate of vocal fold length. This is because the most extreme positions of the mold made contact with the structures typically used to measure vocal fold length, eg, the vocal process and the anterior commissure. However, noisy data at the extremes sometimes necessitated a small reduction of this region to facilitate data analysis.

DATA ANALYSIS, RESULTS, AND DISCUSSION

The first step of the analysis consisted of fitting low-order polynomials to the medial surface of the molds. Polynomials were expressed in the following general form:

$$X(y,z) = \sum_{i=0}^{M} \sum_{j=0}^{N} A_{ij} y^i z^j \qquad (1)$$

where A_{ij} are coefficients determined by computing a best-fit polynomial to the image data by Gaussian elimination.

Best-fit polynomials were computed for each mold. For each glottal configuration, the values of M and N were systematically modified, thus altering the degree of the polynomials in y and z (see equation 1). For every polynomial, the coefficient of determination (COD) was computed to assess its goodness of fit with the data. The COD is a standard statistical term used to assess the goodness of fit of linear and nonlinear models to empirical data. It is

TABLE 1. COEFFICIENT OF DETERMINATION PERCENTAGES FOR THREE MOLDS OF LARYNX ONE

	Open Larynx				*Just Barely Adducted*				*Pressed Arytenoids*			
	Maximum Power in y (M)				*Maximum Power in y (M)*				*Maximum Power in y (M)*			
Maximum Power in z (N)	*0*	*1*	*2*	*3*	*0*	*1*	*2*	*3*	*0*	*1*	*2*	*3*
0		31				23				10		
1	54	89	93		56	92	92		61	83	83	
2		92	93	94		95	96	96.0		95	95	95
3		93	95	96		96	96	96.9		95	95	95
4		93				96				95		

See text for definitions.

defined as follows:

$$\text{(2)} \qquad \text{COD} = 1 - \frac{\sum_i (xi - yi)^2}{\sum_i (xi - \bar{x})^2}$$

where yi refers to predictions from the model, xi refers to the empirical data, and $\bar{x}$ refers to the average value of the empirical data. The value of the COD could range between 0 and 1. A value of 0 did not capture any of the variance of the data (ie, the model was no better than an average value estimate), and a value of 1 gave a perfect match between the model and the data. With a computed table of COD percentages for various values of M and N, one could objectively assess the order of polynomial necessary to fit the data. The results for the 3 molds are shown in Table 1.

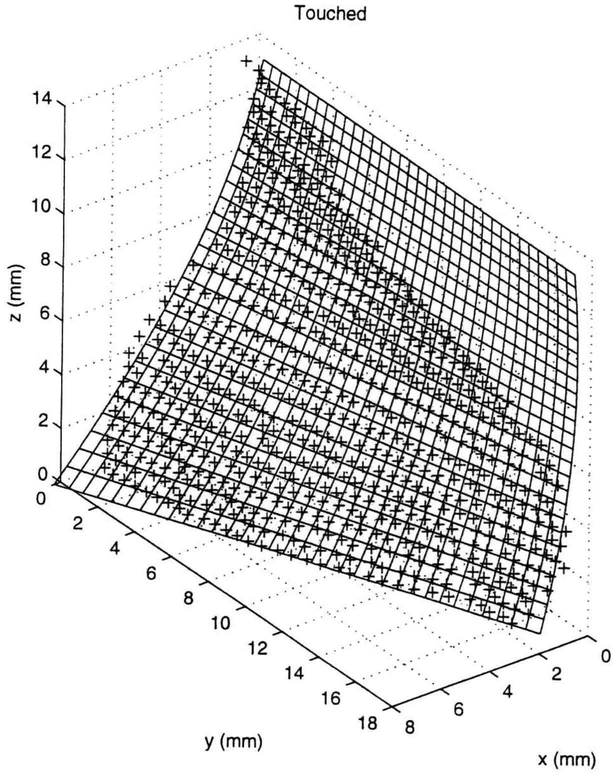
For all of the glottal configurations, the data strongly suggested that the N = M = 1 condition was a satisfactory condition. If either N or M was lowered, the COD dropped dramatically, indicating that the model could no longer adequately explain the data. For N = M = 1, the COD ranged between 83% and 92%. An additional 3% to 8% gain could be obtained by increasing N to 2, suggesting that a quadratic variation in z might also be important in explaining the curvature of the folds. For the most part, only small gains were achieved by further increasing the values of M and N.

Using N = 2 and M = 1, a visual portrayal of the polynomial fit to the data is shown for the adducted and "pressed" conditions, as shown in Fig 4A,B. Notice that for the adducted mold, no data points were available for the superior-anterior portion of the mold. This illustrates a general limitation of the molding procedure: in order for the mold to exist in a particular region, the glottal airway needs to have a finite width (on the order of 0.1 mm). Thus, the mold did not exist (the molding material simply broke off) in any region in which the glottal airway had a width of less than 0.1 mm. For the purpose of data analysis, such regions were zero-padded. While this was a limitation of the procedure, given that the accuracy of the measurements was on the order of 0.1 mm, this was not viewed as a serious limitation, and zero-padding these regions yielded a reasonable estimate of the "missing" data. For the "pressed" mold as shown in Fig 4B, the entire top 5 mm of the data were missing.

For the separated folds, there were no missing data. Figure 4C shows the results of a cubic fit of the z curvature (M = 3 and N = 1) for the top 13 mm of the glottal airway. Although the cubic polynomial (COD = 93.9%) was not a great deal better than the quadratic polynomial (COD = 92.5%) according to the data in Table 1, physically, the cubic yielded a much better representation of the mold over this entire 13-mm region. As can be seen in Fig 4C, the convexity of the folds changed from top to bottom (ie, from concave to convex). A cubic polynomial was necessary to capture this variation in curvature.

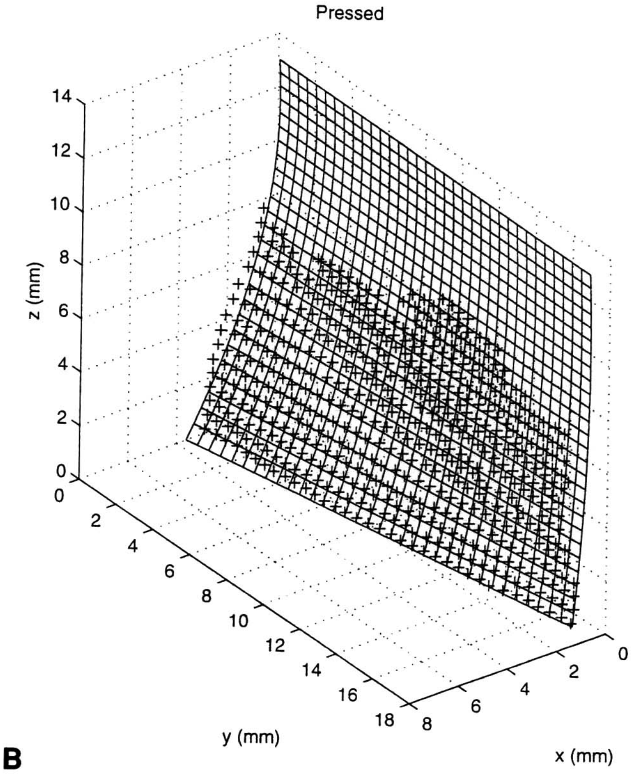
However, as already noted, the focus of this study is on the medial surface of the folds, which may correspond to vibration. Traditionally, it is understood that only the top 3 to 5 mm of the folds is important in terms of vocal fold vibration. For the case of the cubic polynomial, the vertical inflection point was calculated to isolate just the "upper" curvature. The inflection point was 7.61 mm from the top anteriorly, and 8.23 mm from the top posteriorly. Midway along the vocal fold length, the inflection point was calculated to be 7.9 mm from the top. For simplicity, the inflection point was rounded off to 8 mm even. Because the mold captured the top 13 mm of the glottal airway, this inflection point corresponded to roughly the top 5 mm of the mold.

In Table 2, the COD percentages were calculated again with only the data corresponding to the vibrating portion of the molds (the upper 5 mm). With this taken into account, across all glottal configurations, the data suggest that a linear function in y and a quadratic function in z are sufficient to capture the curvature of the folds. This is a preliminary confirmation of the hypothesis proposed earlier by Titze[11] that the y curvature of the pre-phonatory glottis is linear



A

Fig 4. Plus marks indicate 3-D data points of scanned mold. **A)** Glottal configuration with arytenoids "just touching." Mesh corresponds to best polynomial fit for M = 1 (linear in anterior-posterior direction) and N = 2 (quadratic in vertical direction). **B)** Glottal configuration in which arytenoids are "pressed" together 1 mm past "just-touching" configuration. Mesh corresponds to best polynomial fit for M = 1 (linear in anterior-posterior direction) and N = 2 (quadratic in vertical direction). **C)** One-millimeter "open" glottal configuration. Mesh corresponds to best polynomial fit for M = 1 (linear in anterior-posterior direction) and N = 3 (cubic in vertical direction).



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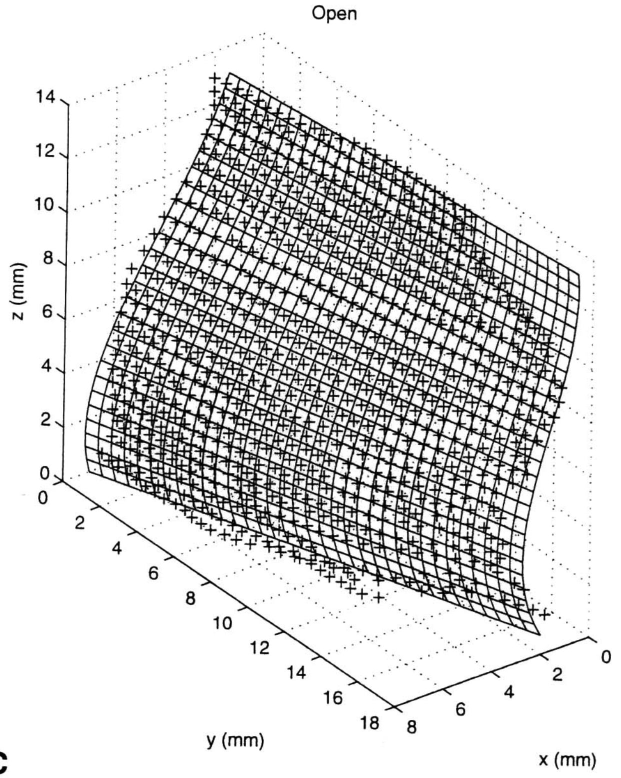


C

and that the z curvature is quadratic. Specifically, he hypothesized that the pre-phonatory glottis could be characterized as follows:

$$(3)\quad X(y,z) = \left(1 - \frac{y}{L}\right)\left[\xi_0 + \left(\xi_c - 4\xi_b \frac{z}{T}\right)\left(1 - \frac{z}{T}\right)\right]$$

where L is the anterior-posterior length of the folds, T is the vertical thickness, ξ_0 is the superior glottal half-width, ξ_c is the convergence coefficient describing the linear variation in z, and ξ_b is the bulging coefficient describing the quadratic variation in z. The physical meaning of these coefficients is further

TABLE 2. RECALCULATION OF COEFFICIENT OF DETERMINATION PERCENTAGES FOR OPEN LARYNX USING JUST UPPER FIVE MILLIMETERS OF MOLD

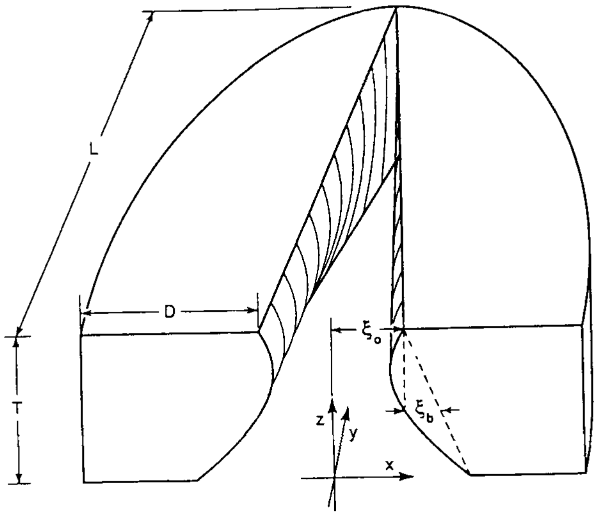
	Maximum Power in y (M)		
Maximum Power in z (N)	*0*	*1*	*2*
0	0.0	44.3	
1	29.1	89.7	90.8
2		96.4	98.0
3		96.6	

See text for definitions.

illustrated in Fig 5.[11]

Although the polynomial of equation 3 is linear in y and quadratic in z, it is obviously more restrictive than the general polynomial of equation 1. However, one advantage of the more restrictive definition is that each parameter has a precise physical interpretation. Of course, the usefulness of this characterization must be judged by how well it matches the empirical data. To perform this evaluation, equation 3 was fitted to the same data as equation 1. In every case, the $z = 0$ level was set 5 mm below the assumed top of the folds. The results of this optimization procedure are shown in Table 3.

By comparing Tables 1 and 3 (Tables 2 and 3, for the case of the open larynx), one can see that the COD percentages drop anywhere from 0.1% to 2.0%. The values of Table 1 (Table 2, for the open larynx) that correspond to Table 3 are found in the column in which $M = 1$ and in the row in which $N = 2$. This slight drop in the goodness of fit did not appear to be



$$g(y,z) = \left(1 - \frac{y}{L}\right)\left[\xi_o + \left(\xi_c - 4\,\xi_b\frac{z}{T}\right)\left(1 - \frac{z}{T}\right)\right]$$

Fig 5. Drawing of pre-phonatory shaping function previously proposed by Titze,[11] illustrating coefficients introduced in equation 3.

TABLE 3. SHAPING PARAMETERS (IN MILLIMETERS) FROM EQUATION THREE AND COD PERCENTAGES FOR THREE MOLDS OF LARYNX ONE

	ξ_0	ξ_c	ξ_b	*L*	*T*	*COD (%)*
Open larynx	1.71	2.75	1.03	20.0	5.00	94.4
Just barely adducted	0.01	1.65	0.16	18.7	4.12	94.7
Pressed arytenoids	0.00	0.26	0.18	20.0	5.07	95.2

L — length; T — thickness; COD — coefficient of determination. See text for other definitions.

significant. Although the fit of either equation was acceptable, the direct physical interpretation of the shaping parameters from equation 3 seemed to outweigh the slight loss in goodness of fit. An illustration of how the "optimized" polynomial (for equation 3) fit the "open" mold is shown in Fig 6.

The shaping parameters of Table 3 appeared to be quite descriptive of the molds, at least for the upper portions of the molds corresponding to the vibrating folds. The open larynx had the greatest glottal half-width ξ_0, the greatest linear convergence ξ_c (the surfaces converged medially when traversing the surfaces in a superior direction), and the greatest quadratic bulging ξ_b. For both the adducted and pressed molds, the glottal half-width was essentially 0, as expected. The glottal convergence of the adducted mold was only 60% of that of the open larynx, and the glottal convergence of the pressed mold was less than 10%. In terms of glottal bulging, both the adducted folds and the pressed folds had small values, ie, less than 20% of that of the open larynx.

One might argue whether the vocal fold length L and the thickness T should have been allowed to vary in the optimization procedure. Certainly, if the model gave large deviations from measured values, the technique would be suspect. There are several reasons why it was thought valid to allow such an optimization here. One reason is that the vocal fold length and effective thickness of the folds might truly vary as a function of glottal adduction. Another reason was that the data did not necessarily extend all the way to the anterior commissure as the model assumes. For example, as indicated in our earlier description of Fig 3, sometimes the length had to be trimmed posteriorly or anteriorly because of noisy data near these end points. By allowing the geometric dimensions L and T to vary, an optimum alignment between model and data was allowed, while still retaining the basic form of the equation. Finally, to compare the optimization results of equations 1 and 3, equation 1 had 6 parameters to vary (for the case in which M equals 1 and N equals 2), whereas equation 3 would have only 3 parameters if the values of L and T were fixed. By allowing a variation in

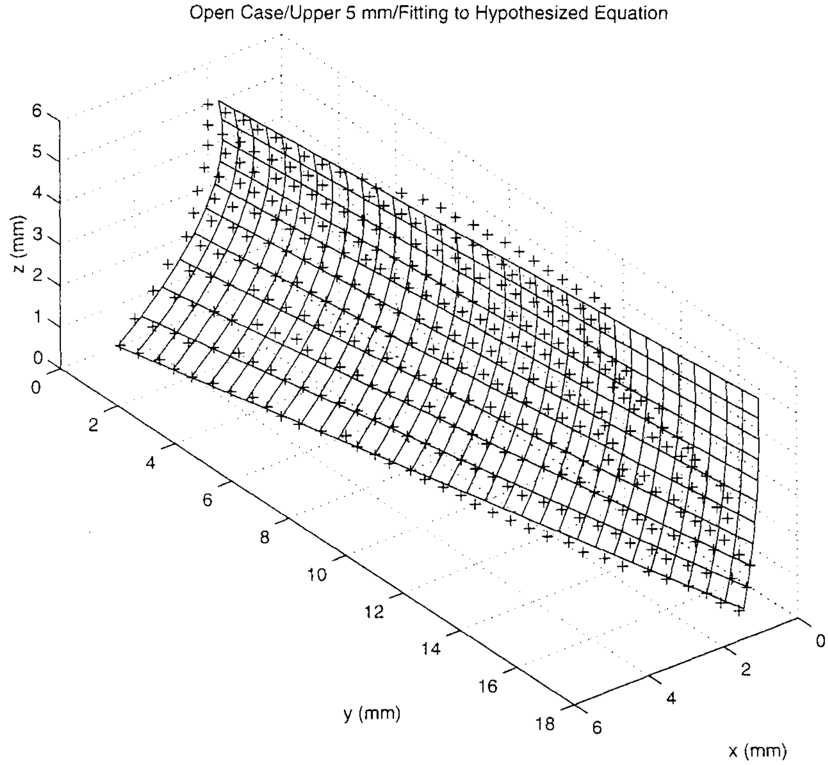


Fig 6. Plus marks indicate 3-D data points of scanned mold corresponding to 1-mm "open" glottal configuration, focusing approximately on top 5 mm, in which most tissue vibration would occur. Mesh corresponds to best polynomial fit to equation 3, using optimized shaping coefficients presented in Table 3.

L and T for equation 3, both equations 1 and 3 had a similar number of parameters to optimize. Optimization results yielded comparable goodness-of-fit statistics for the 2 equations.

SUMMARY AND CONCLUSIONS

A technique was presented for quantifying the prephonatory shape of the vocal folds mathematically on excised larynges. A primary limitation of this method is that the thyroarytenoid muscle is not activated in an excised larynx. However, this is a limitation that can only be overcome with imaging at higher levels of precision than are currently available on human subjects. Thus, a molding procedure was used to capture the shape of the excised larynges. Ultimately, a lead mold was generated, which was subsequently digitized with a 3-D laser striping system with a precision of 0.1 mm. Three molds were created, digitized, and fitted to low-order polynomials.

Through analysis of the COD for various polynomial models of glottal shape, it was argued that minimally, a linear variation in y and z was needed to capture the curvature of the folds. Further modest gains were achieved by allowing a quadratic variation in z. However, any further increase in the order of the polynomial did little to improve the correspondence between model and data. Consequently, on the basis of the 3 molds analyzed in this preliminary study, it was argued that a linear variation in y and a quadratic variation in z was sufficient to capture the curvature of the folds across a range of glottal adductions.

This result is a preliminary confirmation of an earlier hypothesis by Titze,[11] in which he presented an equation (equation 3) to describe the pre-phonatory shape of the folds on the basis of glottal convergence and bulging coefficients. In this study, the coefficients were optimized for each of the 3 molds, and are enumerated in Table 3. These coefficients provided a useful description of the pre-phonatory shape of the vocal folds, and could be directly inserted into our models of vocal fold vibration.

Our technique has been shown to capture the prephonatory glottal shape with a precision on the order of 0.1 mm. With the technique and results presented in this study, we now have the confidence to proceed with further studies in which greater numbers of molds will be generated, digitized, and analyzed. Such investigations are of extreme importance, because initial conditions and boundary conditions are known to have a profound impact on vocal fold vibration, just as they do on many other nonlinear dynamic systems.

ACKNOWLEDGMENTS — Special acknowledgment is given to the Department of Artificial Intelligence of the University of Edinburgh for use of their laser striping system. The authors also thank Karin Titze Cox, whose earlier investigations (K. A. Titze and I. R. Titze, unpublished manuscript) yielded fruitful insights into the present study, and to Cindy Steffensmeier, who manually digitized one of our initial molds using a 3-dimensional micrometer.

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