The effects of phonosurgery on laryngeal vibration: Part I. Theoretic considerations

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Surgical manipulation of the laryngeal framework (phonosurgery) is rapidly gaining interest and attention. To date, however, a comparative objective evaluation of the various phonosurgical techniques has not been reported. A theoretic model of the larynx, a four-mass model based on the work of Ishizaka (J Acoust Soc Am 1976;60:1193-8) and Koizumi et al. (J Acoust Soc Am 1987;82:1179-92), was developed and adapted to simulate laryngeal biomechanical behavior, as understood by current research. The model was then applied to a comparative evaluation of phonosurgical techniques. Input parameters that correlate laryngeal function and model simulation were developed. Surgical procedures were categorized according to their effect on these parameters. A model simulation of these techniques allowed comparison and prediction of the results of phonosurgery and a better understanding of the issues involved with surgical alteration of the voice. (OTOLARYNGOL HEAD NECK SURG 1990;103:380.)

In 1974 Isshiki et al.[1] coined the term "thyroplasty," referring to a group of surgical techniques that alter the shape of the thyroid cartilage to change the phonatory function of the larynx. These phonosurgical techniques have been further developed[2,3] and initial results reported.[4,5] In the United States, interest has grown in surgery of the laryngeal framework, primarily because of the inherent problems in predicting long-term effects of standard rehabilitative techniques, such as polytef (Teflon) injection reported by a number of surgeons.[6,7] Also, while animal studies of nerve transfer reinnervation have shown promise,[8-10] results in human beings have been less encouraging.[11,12] Recently, some of the methods of Isshiki have been adopted, modified,[13-19] then applied to a variety of vocal disorders involving abnormal pitch range.

"Vocal pitch disorders" comprise several different conditions.[20] Generally, they refer to any alteration in the pitch and quality of voice. For males, mutational voice disorders cause too high a pitch. In contrast, female patients develop a low pitch from adrenogenital syndrome or as a side effect of anabolic steroid use. In the elderly, laxity of vocal ligaments may produce flaccid larynges,[14] and neuromuscular diseases can produce a variety of voice disorders.[21] Vocal cord paralyses are a well known cause of vocal pitch disorders. The pathophysiology of vocal fold paralyses have been studied in detail.[22-24] However, how laryngeal paralyses affect laryngeal vibration are not as well understood.

Initial research by Tanabe et al.[25] and others[26-28] contributed to an understanding of the mechanisms of pitch control of the larynx. The fundamental frequency or pitch is controlled by the stiffness or tension in the vocal fold. Stiffness changes are said to result from intrinsic muscle activity whereas changes in tension occur as a result of extrinsic muscle activity.[29] Isshiki et al.[26] found that the pitch of voice could be altered by asymmetric adjustments in the tension of the vocal folds without disrupting regular vibration. This work led to the notion that the laryngeal framework can be unilaterally (asymmetrically) as well as bilaterally altered and still produce normal phonation. Further investigation into the nature of the relationship between laryngeal tension and vocal pitch has been the subject of continuing research efforts.[30,31]

No less important than physiologic studies in elucidating mechanisms of pitch control is theoretic modeling of laryngeal function. Several theoretic models of vocal fold vibratory behavior have been developed applying knowledge of acoustics and laryngeal biomechanics to describe vocal fold vibration.[32,33] The most well known of these is the two-mass model of Ishizaka and Flanagan,[32] based on theoretic work of Ishizaka

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Table 1. List of four-mass model parameters and variables used to simulate effects of phonosurgical procedures

Four-mass model parameters	Mathematical variables	Larynx function paradigm
G	A_{g0}	Vibratory gap
Q	$k_{x2,4}$M, D	Cricothyroid contraction
P	$k_{x1,3}$ Psub	Vocalis contraction and subglottic pressure
T	$k_{x1,3}$	Vocalis tension

and Matsudaira.[34] The two-mass model is based on a mechanical simulation of the observed phase difference between the lower and upper margins of the vocal folds during phonation. Stevens[35] described the significance of the two-mass model in advancing our understanding of laryngeal function. He pointed out that by representing the vocal fold as a lumped mass model of coupled masses and springs, a significant transfer of energy from air flow to the mechanical vibratory system is achieved by motion of the upper and lower edges of the fold that are out of phase. This model has been used in speech synthesis, analysis of phonation, and as a standard of comparison with other phonatory models.[36,37] Further refinements of the two-mass model by Koizumi et al.,[38] to include vertical as well as horizontal displacements, have yielded perceptually more human-sounding synthetic speech, as well as a more realistic representation of vocal fold motion. Theoretic models allow the prediction of acoustic and biomechanical effects through control of model parameters. Of interest is the comparison of data from theoretic models to available clinical objective measures of vocal fold movement.[39]

Progress has been made in the development and use of clinical techniques for the evaluation of vocal function.[40] Photoglottographic and electroglottographic signals have shown promise as methods to evaluate laryngeal function.[41,42] Various quantitative parameters, such as open quotient (OQ) and speed quotient (SQ), can be derived from the glottographic tracings.[40] OQ is defined as the ratio of the time the glottis is open during the vibratory cycle. An increase in OQ generally reflects breathy phonation; a maximum OQ of 1.0 means the vocal folds never touch during phonation. SQ gives information about the vocal folds while they are apart. It is the ratio of the time the folds are opening over the time they are closing. Increased SQ may be related to

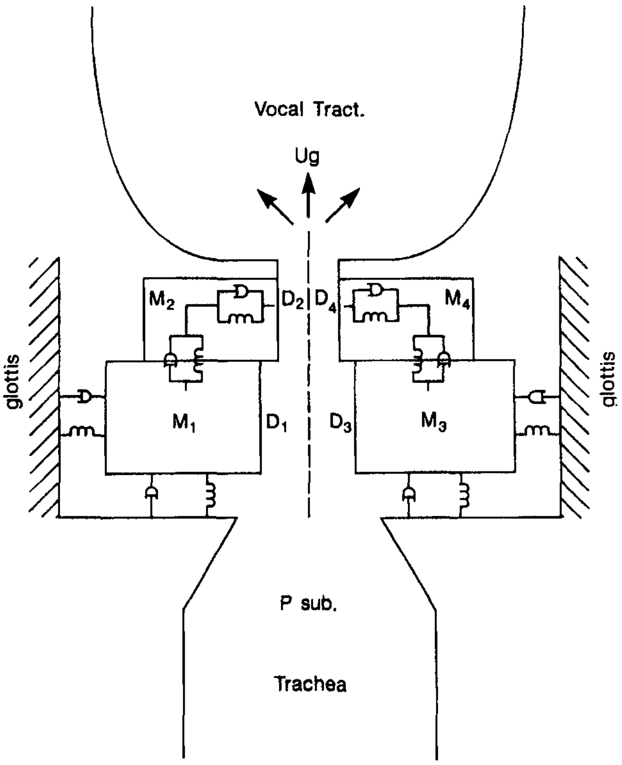

Fig. 1. Mechanical configuration of four-mass model of the larynx, modified after Ishizaka and Isshiki[33] and Koizumi et al.[38] *Psub* = Subglottic pressure; U_g = glottal flow; *M* = mass; *D* = vertical thickness.

the "brightness" of voice, as reflected by more energy in spectral harmonics.[43,44] Mean airflow rate and phonation time also have been used to quantify laryngeal function.[40] Acoustic analyses of voice have also received research attention, but clinical application of acoustic measures in general has been limited.[45-47] A multidimensional approach using a number of objective measures to describe laryngeal dysfunction is gaining acceptance.[48-50] Hirano[51] has suggested an outline of tests to be used in analysis of phonatory function, that includes some of the objective measures discussed. A major factor limiting comparison of phonosurgical techniques in the past has been a lack of use of these standardized measures, and a lack of accepted criteria for comparison among clinicians.

METHODS

The Koizumi modification of the two-mass model[38] was chosen for use in our study. Its mechanical arrangement, in which the upper mass is coupled solely to the lower mass (Fig. 1) rather than doubly coupled to the side wall and lower mass, appeared to be a more realistic representation of the structure and motion of the vocal folds. The model also allowed for vertical

Table 2. List of phonosurgical procedures

Pitch-elevation procedures	Pitch-lowering procedures	Treatment of glottic incompetence
1. Cricothyroid approximation (Isshiki Type IV)[1] 2. Anterior commissure lengthening a. Isshiki alar expansion[5] b. Tucker superior flap[14] c. LeJeune inferior flap[13]	1. Isshiki thyroplasty Type III [1] 2. Cricothyroid myotomy[5]	1. Polytef/Teflon injection[6] 2. Nerve reinnervation[11,12] 3. Medialization laryngoplasty[2,15] 4. Arytenoid adduction[3]

Table 3. *Predicted effects of phonosurgical procedures on four-mass model parameters*

Types of procedures	G	Q	P	T
Pitch-elevation procedures				
1. Cricothyroid approximation	↓↓	↑↑↑		
2. Anterior commissure lengthening		↑↑		↑↑
Type a. (Isshiki)	↓	↑↑		↑
Type b. (LeJeune)	↓	↑		↑↑
Type c. (Tucker)	↓			
Pitch-lowering procedures				
1. Anterior commissure shortening (Isshiki Type III)				
a. Unilateral	↑	↓		
b. Bilateral	↑	↓↓		
2. Cricothyroid myotomy	↑↑	↓↓↓		
Medialization procedures				
1. Polytef/Teflon injection	↓↓		↑	
2. Medialization laryngoplasty	↓		↑↑	
3. Arytenoid adduction	↓			↑
4. Nerve reinnervation	↔		↑↔	

G, Vibratory gap; Q, cricothyroid tension; P, subglottic pressure and vocalis stiffness; T, vocalis stiffness.
Arrows indicate the magnitude of change (increase or decrease) in parameter; e.g., ↑ = small increase; ↑↑ = moderate increase.
↔ = the change in parameter is variable.

displacement of the cords. Vertical cord displacement is believed to be of importance in evaluation of laryngeal paralyses.[52]

The Koizumi model was expanded to simulate four-mass motion of the larynx rather than the usual two-mass motion. This was done by following theory applied to a similar model of pathologic phonation,[33] after the Ishizaka and Flanagan two-mass model.[32] This allowed the independent variables of the model to be changed asymmetrically. Forcing relationships governing mass motion during collision developed by Ishizaka and Isshiki[33] were followed. The mathematic equations comprising the model were programmed in Fortran and the output displayed and stored on an IBM-AT compatible computer. In brief, the model worked as follows. Subglottic air pressure displaced the masses apart and set them in motion on their connected springs. Mathematic relationships described the motion of the masses. Differences between the upper and lower mass variables created a phase lag of the upper mass. Air flow was induced in the glottal orifice that was periodically interrupted by collision of the masses. The input variables included the masses and their associated spring and damping constants, subglottic pressure or Psub, and the interglottal distance between the masses, termed the vibratory gap (A_{g0} in previous studies).

The model parameters used are listed in Table 1. These are described as follows. First, parameter *G* was a measure of the gap between the vibrating masses during phonation. In previous studies, this was termed A_{g0}. It has been shown to correspond well with glottal gap or chink, and an increase in this parameter has been

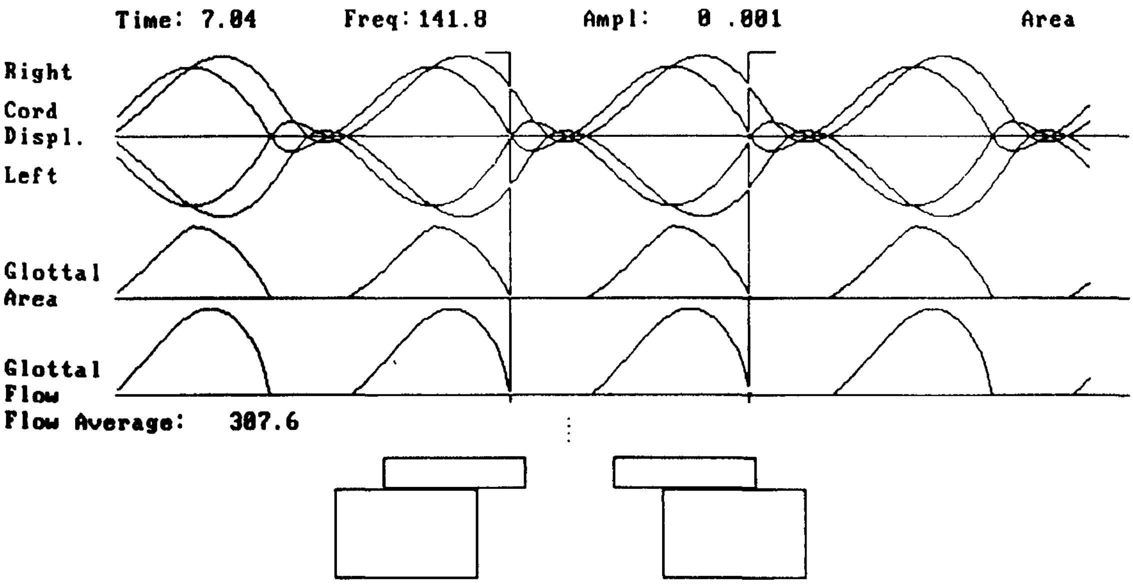

Fig. 2. Computer output of four-mass model, baseline "normal male" parameters. Shown are displacement of the lower and upper masses of each vocal fold, glottal area and glottal flow waveforms. Motion of the masses is also depicted.

associated with perception of a breathy voice.[4,33] Parameter Q was adapted from the Ishizaka and Flanagan two-mass model.[32] Q was used as a constant term multiplied by spring stiffness k and divided by mass m to change frequency of oscillation. In addition, Q also affected vertical thickness d. In previous studies, this parameter was shown to be analogous to cricothyroid tension.[26,33] The parameter has physiologic correspondence since observations have described a decrease in mass and thinning of vocal fold mucosa during cricothyroid contraction.[53]

In our study, Q was applied to the Koizumi model in a fashion similar to that of Ishizaka and Flanagan, except that it was multiplied only by variable k_x of the upper mass spring, not the lower springs. The parameter P was related to variable k_x, spring stiffness of the lower masses, and subglottic pressure Psub. This is analogous to vocalis muscle contraction, so that as stiffness of the lower masses increased, subglottic pressure rose accordingly. Results of recurrent laryngeal nerve stimulation in the in vivo canine model agree with this subglottic pressure-stiffness relationship.[30] Parameter T was related solely to lower mass spring stiffness k_x, with no associated subglottal pressure rise. This reflected vocalis muscle tension exerted by longitudinal stretching, with no changes in mass or stiffness that would affect subglottic pressure. Parameters G, P, Q and T served as input variable combinations in order to model phonosurgical procedures with the four-mass model.

Phonosurgical procedures are grouped as listed in Table 2. These were divided into categories as procedures to restore glottal competence and procedures to change vocal pitch. The effect of phonosurgical techniques on four-mass model vibration was determined by variation in the model's mathematic input parameters (G, P, Q, T). These parameters were correlated with results of direct laryngeal experimental results from in vivo studies of canine and human phonation. Phonosurgical procedures were categorized according to the effect each one was judged to have on the model parameters G, P, Q, and T. Results are listed in Table 3. For example, in the pitch adjustment procedures, a cricothyroid myotomy was judged to decrease parameter Q whereas a cricothyroid approximation increased Q. In contrast to the clear differences cricothyroid surgeries had on parameter Q, the anterior commissure lengthening procedures were judged to have subtly different influence on the other phonation parameters. The inferiorly based flap of LeJeune et al.[13] was predicted to have greater stretching on the upper margin of the vocal folds, to thus yield more influence on cricothyroid tension than on vocalis stiffness. The reverse was true for the superiorly based flap of Tucker.[14] The biparasagittal split and expansion of Isshiki et al.[5] was judged to increase the effect of cricothyroid and vocalis tension more equally, to result in a Q and P adjustment between LeJeune et al.'s and Tucker's procedures. The medialization procedures were predicted to have varying degrees of effect on

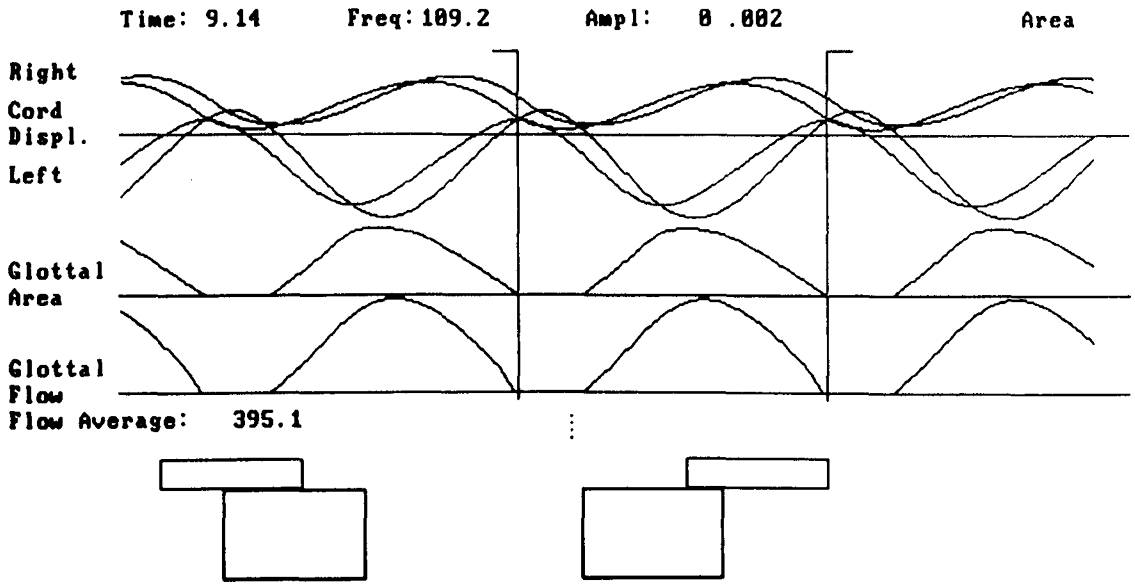

Fig. 3. Computer output of four-mass model, with parameters changed to simulate right recurrent nerve paralysis. Changes in mass displacement, glottal area and flow waveforms are seen (compare Fig. 2).

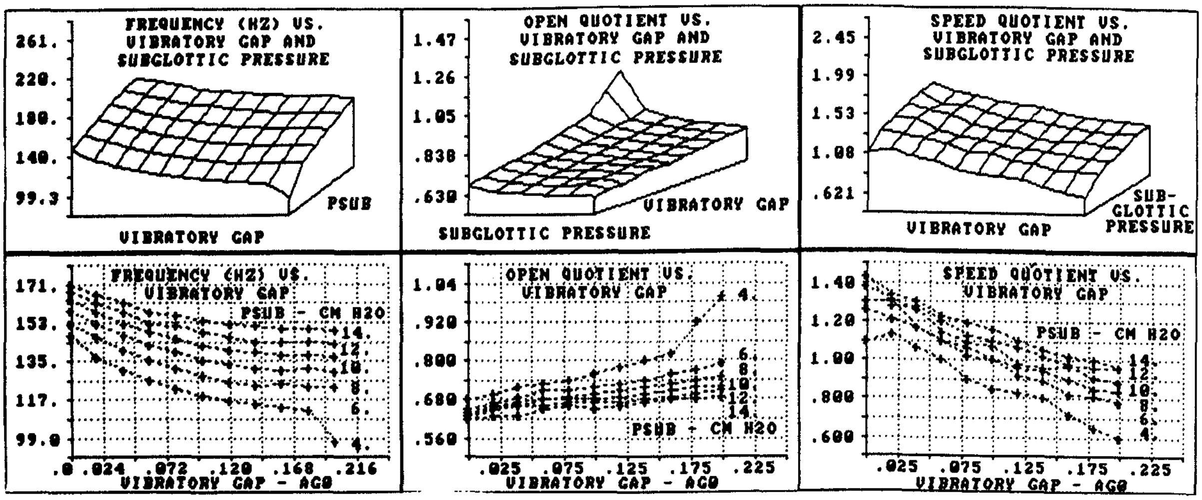

Fig. 4. Four-mass model frequency, open quotient and speed quotient data for variations in vibratory gap *(G)* and subglottal pressure *(Psub)*.

parameters *T*, *P*, and *G*, as seen in Table 3. For example, the nerve reinnervation procedure was judged to increase vocalis muscle tension, but not have as much effect on closing the vibratory gap as polytef (Teflon) injection.

To study the data output of model simulations, a number of objective measures of vocal fold vibration were used. They included fundamental frequency F_0, or pitch, and mean airflow rate (MFR). In addition, open quotient (OQ) and speed quotient (SQ) were determined from the glottal area waveform. A spectral analysis of the glottal flow waveform was performed as well. From the spectral analysis, a spectral measure called the (F_0-H_2) difference was determined for each case. (F_0-H_2) is defined as the difference in spectral energy between the fundamental frequency and the second harmonic, in decibels (dB).

Phonosurgical procedures were basically divided into pitch adjustment techniques and vocal fold medialization procedures. Data from the pitch adjustment procedures were compared to normal male baseline model parameters. Results for medialization procedures were

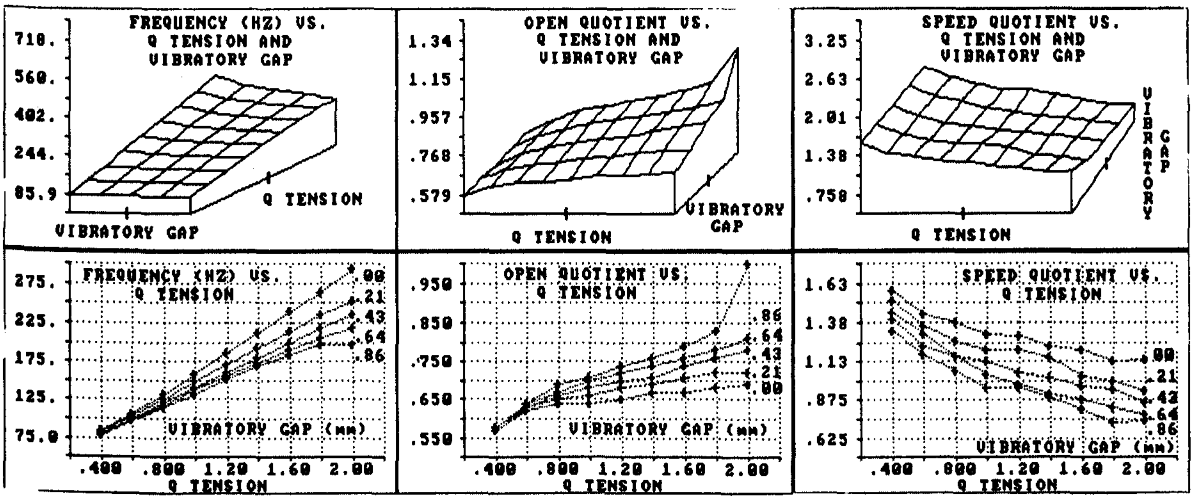

Fig. 5. Four-mass model frequency, open quotient and speed quotient data for variations in parameter Q and vibratory gap *(G)*.

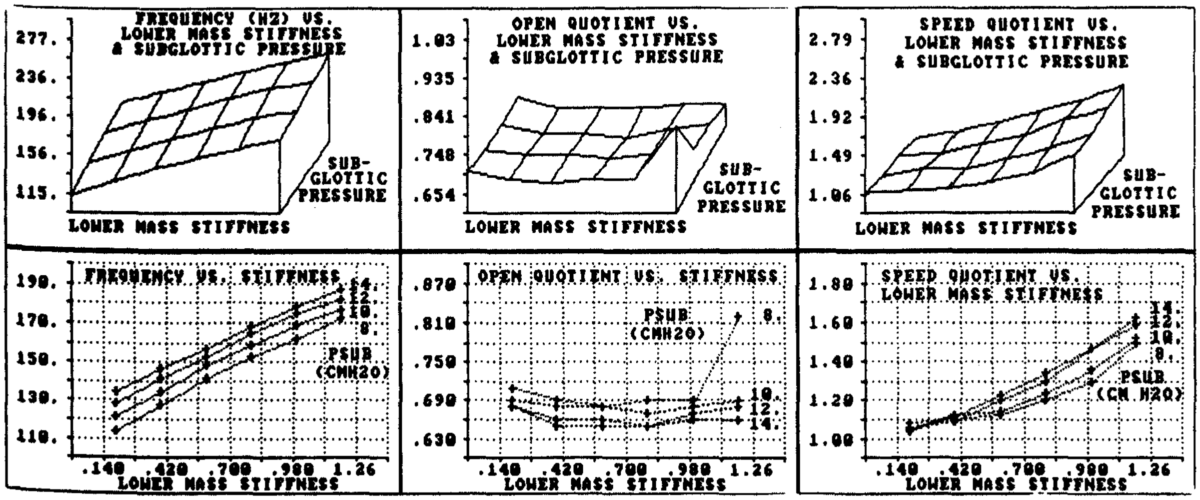

Fig. 6. Four-mass model frequency, open quotient and speed quotient data for variations in lower mass stiffness (parameter T) and subglottic pressure *(Psub)*.

determined by their effects on a simulated recurrent laryngeal paralysis. This was done by increasing parameter *G* and decreasing *P*. The effect of each medialization procedure was then tested by applying criteria for the procedure from Table 3 to the model paralysis simulation. Percent change in pitch (fundamental frequency-F_0), open quotient, speed quotient, mean flow rate, and (F_0-H_2) difference were then calculated from the computer-generated glottal and flow waveforms for all phonosurgical simulations. Waveform samples were then used as source input to a vocal tract synthesizer to generate synthetic speech for perceptual comparison.

RESULTS

The results of computer modeling of phonosurgery were divided into four areas of investigation. *First,* the behavior of the four-mass model was observed during changes in vibratory gap, subglottic pressure, *Q* (upper mass) symmetric tension, and *T* (lower mass) symmetric tension. *Second,* baseline data parameters were calculated for simulated normal male phonation and simulated unilateral recurrent laryngeal nerve paralysis. *Third,* by variation of parameters as listed in Table 3 to simulate phonosurgery, the laryngeal vibratory and acoustic data for each simulated procedure were measured. *Finally,* an estimate of perceptual changes re-

Table 4. Results of four-mass model simulation baseline phonation output*

Baseline parameters	Freq	OQ	SQ	MFR	F_0-H_2
Normal male phonation	142	0.68	1.10	308	9.3
Recurrent laryngeal paralysis	108	0.82	0.71	392	25.7

*Baseline parameters for normal male speaker and simulated recurrent laryngeal nerve paralysis: F_0, Fundamental frequency in Hz; *OQ*, open quotient; *SQ*, speed quotient; *MFR*, mean flow rate in cc/sec; F_0-H_2, difference between spectral amplitudes of fundamental frequency and second harmonic in dB.

Table 5. Results of predicted four-mass model output effects for phonosurgical procedures on laryngeal vibratory measures

Types of procedures	Pitch (%)*	OQ	SQ	MFR	F_0-H_2
Pitch-elevation procedures					
1. Cricothyroid approximation	+33%	0.71	1.06	198	16.4
2. Anterior commissure lengthening					
Type a (Isshiki)	+42%	0.72	1.22	169	16.7
Type b (LeJeune)	+36%	0.71	1.15	192	13.8
Type c (Tucker)	+29%	0.72	1.30	201	16.5
Pitch-lowering procedures					
1. Anterior commissure shortening (Isshiki Type III)					
a. Unilateral	−12%	0.70	1.22	398	15.8
b. Bilateral	−23%	0.65	1.16	450	16.7
2. Cricothyroid myotomy	−22%	0.76	0.58	450	25.3
Medialization procedures					
1. Polytef/Teflon injection	+43%	0.66	1.30	215	15.0
2. Medialization laryngoplasty	+54%	0.66	1.44	206	13.9
3. Arytenoid adduction	+35%	0.67	1.17	152	14.1
4. Nerve reinnervation	+22%	0.70	1.06	333	18.5

*Percentage of pitch change (fundamental frequency in Hz) from baseline (Table 4).
OQ, Open quotient; *SQ*, speed quotient; *MFR*, mean flow rate in cc/sec; F_0-H_2, difference between spectral amplitudes of fundamental frequency and second harmonic in dB.

sulting from change in speed quotient was evaluated by measuring (F_0-H_2) differences and listening to synthesized speech samples.

With regard to the first area, the behavior of the four-mass model is shown in Figs. 2 through 6. Fig. 2 displays the four-mass model typical waveform computer output, which included right and left displacement of the upper and lower masses, glottal area, and glottal flow. Graphic cursor control of the computer display was used to measure amplitudes and time intervals. Animation of the movement of the four masses was also displayed in real time on the computer monitor. Simulation of right recurrent laryngeal nerve paralysis is shown in Fig. 3 by unilateral variation of parameters *G* and *P*. Asymmetric excursions of the right and left masses was seen with flattening and shift in the peak of the glottal area and flow waveforms to the left, as compared with Fig. 1. In Fig. 4, changes in pitch (fundamental frequency), open quotient, and speed quotient during changes in vibratory gap and subglottic pressure are displayed. Pitch rose with increased subglottic pressure and fell with increased vibratory gap. As expected, open quotient rose with increased vibratory gap and fell somewhat with subglottic pressure increases. The speed quotient demonstrated the opposite behavior; it fell with widening vibratory gap and rose with subglottic pressure increases. Figure 5 contains information on *Q* tension changes. Marked increase in pitch was seen with rising *Q* tension. The changes in open quotient and speed quotient are the opposite from those seen with vibratory gap. Open quotient rose with increasing *Q* tension and speed quotient fell. In Fig. 6, data are displayed on changes in *T* (lower mass) tension. Frequency rose with increasing *T*, though not as much as

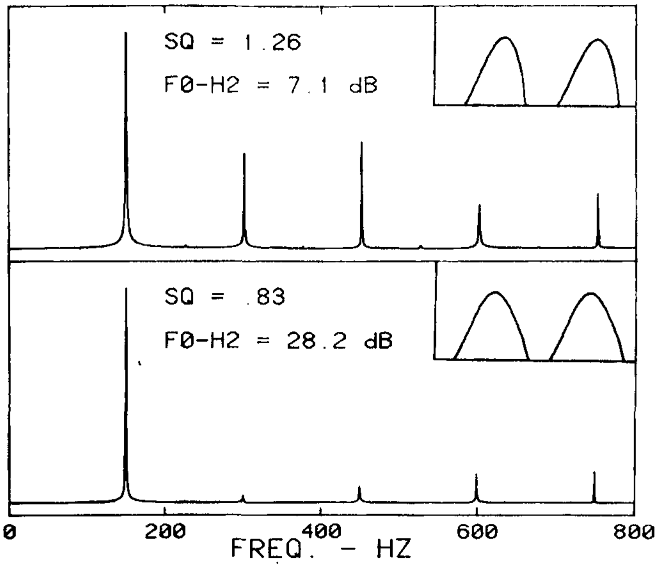

Fig. 7. Effects of speed quotient on glottal acoustics. Spectral plots of glottal flow waveforms that have the same pitch but differ in speed quotient. (F_0-H_2) difference reflects difference in spectral energy between fundamental frequency and second harmonic. Inset in the plots are the glottal flow waveforms. The lower waveform with SQ = 0.83 shows the peak of the wave shifted to the left.

with Q tension. Open quotient remained relatively unchanged and speed quotient rose with increasing T, the opposite of Q tension results. These results were compared with other laryngeal models as discussed below.

Next, we examined baseline vibratory characteristics of a simulated "normal" male. Table 4 shows pitch, open quotient, speed quotient, mean flow rate, and (F_0-H_2) difference as calculated from the computer data. Also shown are the data of a simulated recurrent laryngeal nerve paralysis. A decrease in pitch was seen with a decrease in speed quotient, increase in mean flow rate, and increase in (F_0-H_2) difference, associated with the glottal area and flow waveforms seen in Fig. 3.

Table 5 lists each phonosurgical procedure and the results of simulation of phonation after changing parameters, as previously described. In general, a pitch rise was seen in the pitch elevation procedures, a fall in pitch from the pitch lowering simulations, and a pitch rise with associated speed quotient shift from the medialization procedures.

Finally, effects of speed quotient on acoustics were examined. Figure 7 shows example spectral plots of glottal flow waveforms and (F_0-H_2) differences on two differing waveforms. These tracings have the same pitch, but differ in their speed quotients. In the flow waveform with the lower speed quotient, the peak appears "shifted to the left." The spectral plots show the waveform with the lower speed quotient to have less amplitude of harmonic frequencies. This lowering of harmonic amplitudes is reflected in a larger (F_0-H_2) difference. Perception of the synthesized speech from these samples confirmed that the lower speed quotient waveform sounded more muffled and the higher speed quotient sample sounded brighter.

DISCUSSION

Evaluation of the four-mass model results must first include an assessment of the ability of the model to simulate vocal fold vibration. A comparison of the results of simulated phonosurgical procedure outcomes will be discussed in the context of the limited available data from the literature. Finally, implications of these theoretic results and future directions of research in phonosurgery and laryngeal function will be addressed.

In recent years, much discussion and review of laryngeal models has ensued.[35,39,54] These exchanges have centered around the advantages and limitations of current models of vocal fold vibration. In addition to "lumped mass" models,[35] such as the four-mass system used in our experiments, a "continuum" model has been developed by Titze.[36] The continuum model attempts to define and model the tissue mechanics as well as the aerodynamics[54] in order to follow Hirano and Kakita's[55] functional description of the "body-cover" relationship of the vocalis muscle and vocal ligament to the overlying mucosa. The ongoing discourse about theoretic models concerns the ability of the models to accurately predict results of direct physiologic experimentation and readiness of application to clinical research.[54] In this regard, results of model simulations should be considered in light of the limitations of a particular model's ability to simulate vocal fold vibration.

The two-mass model of Ishizaka and Flanagan has several advantages, as well as some disadvantages applicable to our experimental design. The Ishizaka and Flanagan model is conceptually more understandable than the continuum model because of the smaller number of variables needed to describe the mass motion. It has been used in a wide variety of laryngeal and speech research settings. Because an earlier version of the two-mass model had been used in simulation of pathologic phonation by Ishizaka and Isshiki,[33] it was believed our phonosurgical simulations could be more readily compared with their data. The recent improvements in the two-mass model by Koizumi et al.[38] were applied in this study. The Koizumi model allows for vertical cord motion, which we considered relevant for simulation of pathologic phonation. Our results of glottal area and flow waveforms, with changes in vibratory gap, subglottic pressure, and asymmetric Q tension, agree well with previous data.[32,33] The two-mass model is limited in certain respects for our purposes. It has been described as a "cover-only" model,[39] which may limit the extent to which large tension asymmetries can be simulated. The glottal orifice is in a rectangular shape. The masses are either in contact or apart. This limits modeling of anterior-posterior defects in glottal closure, such as bowing. The current model has some limitations in calculating pressure drops within the glottis because the interface between the upper and lower mass on each side must be on the same horizontal plane. This imposed vertical symmetry limits modelling of vocal folds on different levels. Despite these shortcomings, our model was able to generate useful data in simulating asymmetric laryngeal tension and phonosurgical procedures.

Some interesting findings were noted in the modelling of recurrent laryngeal nerve paralysis. A marked drop in pitch was seen. This was also reported in simulated recurrent laryngeal nerve paralysis in the in vivo canine model.[24,56] On the other hand, in a sample of patients with recurrent laryngeal nerve paralysis studied by Hanson et al.,[49] a higher average pitch was measured than an unmatched group of normal speakers. This implies that patients with laryngeal nerve paralysis may use compensatory mechanisms (i.e., high cricothyroid *muscle tension) to increase contact of the vocal folds* and compensate for the paralyzed vocal fold. This compensating increase in pitch was also seen in the in vivo canine model when recurrent laryngeal nerve paralysis was simulated with high cricothyroid tension.[24]

The results of pitch adjustment procedure simulations were compared with data reported by Isshiki et al.[5] for both pitch lowering and pitch elevation techniques. Pitch lowering procedures have been performed for mutational voice disorders and vocal cord atrophy. The pitch of the voices of patients with mutational voice disorders dropped an average of 131 Hz, whereas the pitch of voices of patients with vocal cord atrophy dropped 67 Hz. A greater drop was seen in patients who had bilateral type III thyroplasties than in those who had unilateral. Our data agree with the range of pitch drop observed in Isshiki et al.'s vocal cord atrophy patients. The group with mutational voice disorders may have had additional overriding factors that accounted for the greater pitch drop seen after surgery. These other factors are probably related to the high success rate obtained in the nonsurgical treatment of this condition, as reported by others.[57,58] The computer simulation of cricothyroid myotomy yielded a breathy voice with high mean flow rate and low speed quotient. The model simulation may thus help explain why the one myotomy case Isshiki et al.[5] reported also required a medialization procedure. Our model confirms good pitch lowering results with thyroplasty type III. Isshiki et al. have reported cartilage implantation medialization procedures for wide vibratory gap after bilateral thyroplasty type III. In our simulation of bilateral procedures, a high mean flow rate resulted from a wide vibratory gap (Table 4). In these cases, an adjunctive medialization procedure may be required.

Pitch elevation procedure simulations also compare favorably with Isshiki et al.[5] They reported an average pitch elevation of 31% with cricothyroid approximation, treating both androphonia and unilateral superior laryngeal nerve paralysis. The qualitative reports of LeJeune et al.[13] and Tucker[14] permit no direct comparison. Model simulation predicts that Isshiki's technique of bilateral alar expansion would result in the greatest pitch change of the three types of anterior commissure lengthening approaches (Table 5).

Vocal fold medialization simulations also permitted interesting comparison with reported results. Crumley et al.[12] state that Teflon injections may improve symptoms of cough, aspiration, and loudness of voice, but are often unsuccessful in restoring vibratory behavior of the larynx.[12] Reports of spectrograms of Rontal et al.,[59] after Teflon injection displayed improvement in breathiness, but provided no information on vocal fold vibration. A case report by Reich and Lerman[60] of a patient with longstanding idiopathic recurrent laryngeal nerve paralysis before and after Teflon injection showed a decrease in pitch, increase in amplitude of spectral harmonics from 2000 Hz to 3500 Hz, and improvement in listener-rated perception of hoarseness, roughness, and pleasantness. In the four-mass model simulations, elevation of pitch to normal range was noted (Table 5). This was closely related to closure of the vibratory gap, as reflected in the mean flow rate. Speed quotient rose significantly, with little change in open quotient. Similar changes in pitch and speed quotient were reported by Trapp et al.[56] after Teflon injections in the in vivo canine model. Again, in cases in which pitch drops after a cord medialization procedure, compensatory pitch elevation mechanisms may no longer be required and the patient readjusts laryngeal tension to yield a pitch at his or her normal range. The reinnervation procedure in the simulation appeared comparable to other techniques to the extent that the reinnervated cord adducted and closed the vibratory gap. The increase in speed quotient seen in all cord medialization simulations provided useful insights into acoustic perception of voice.

A comparison of speed quotients in two otherwise similar glottal waveforms showed the tracing with the lower speed quotient shifted to the left, or less than 1.0. This indicated a slow phase of glottal closure when compared to opening. In a study on the production of breathy vowels, Huffman[44] described such a shift to the left of the flow waveform, in association with an increase of the (F_0-H_2) difference. Her findings can be explained by the slower cord closure, resulting in a glottal flow that lacks energy to amplify higher spectral harmonics. The model thus elucidates understanding of the spectrogram results of Rontal et al.[59] An increase in speed quotient associated with faster cord closure after injection yields higher spectral energy, as shown in the post-Teflon spectrograms. The (F_0-H_2) difference appeared to be well-correlated with changes in speed quotient in our model.

This theoretic study was undertaken with the expectation that comparison of acoustic and vibratory measures associated with the various phonosurgical procedures would yield information with which to categorize the primary effects of the surgeries on the larynx. Analysis of the data has revealed differences in laryngeal function related to the type of procedure chosen. It thus follows that qualitative anecdotal reporting of results of phonosurgical intervention in small numbers of patients will only serve to add confusion in regard to indications for use of the different procedures. Results of this theoretic study emphasize the need to objectively and quantitatively evaluate results of phonosurgical intervention on randomized patient groups in order to understand and guide intelligent choice of techniques. This investigation has produced the framework on which future studies (Part II) will explore the effects of changes in tension and stiffness on laryngeal vibration in vivo.

CONCLUSIONS

Changes in laryngeal tension, vibratory gap, and subglottal pressure simulated on a theoretic four-mass model of the vocal cords were able to predict the effects of phonosurgery on laryngeal vibration. The model yielded insights into the nature of laryngeal vibration during states of asymmetric tension and demonstrated the usefulness of various measures of glottal vibration. The direct in vivo measurement of laryngeal tension is a goal of future studies.

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