Intraoperative Measurement of the Elastic Modulus of the Vocal Fold. Part 2. Preliminary Results

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This paper presents initial clinical experience using a device capable of measuring the transverse elastic modulus of the vocal fold. These initial results indicated that the device may be useful in determining stiffness inequalities between the vocal folds.

INTRODUCTION

The purpose of this ongoing work is to test the hypothesis that the intraoperative measurement of the transverse (horizontal) Young's modulus of the human vocal folds will improve phonosurgical results for glottal incompetence caused by unilateral vocal fold paralysis. The examination of this hypothesis included the development of a device to:

1. Measure the vocal fold's elastic modulus rapidly and easily during surgery in humans.

2. Be maneuvered easily into place to make measurements during laryngeal surgery at frequent intervals.

3. Significantly improve surgical outcome for glottal incompetence.

Central to the idea of improving surgical outcome by measuring Young's modulus is the intraoperative monitoring of phonosurgery. For example, Fukuda[1] developed an intraoperative monitoring technique in which an external vibrator was used to create a wave motion in the vocal folds. The motion was then monitored during surgery by stroboscopy to determine when symmetrical vibration was obtained. A weakness in this technique is that the relationship of externally induced vibration to natural cord vibration is unclear. A preliminary study by LeJeune[2] reported on a device which measured the degree of vocal ligament tightening during surgery on the laryngeal framework. The article gives strong support to the idea that a device that could objectively measure an endpoint for surgical manipulation would be a valuable intraoperative tool. However, LeJeune's device only measured strain, not stress, and the strain was determined by pinching the fold, and thus could produce injury to the vocal fold. Vocal fold vibration was monitored in a human intraoperatively during general anesthesia by insufflating air rostrally through the vocal folds while vibration was produced by manually adducting the arytenoids together to allow an intraoperative evaluation of vocal function.[3] This method was used to monitor the endpoint for injecting Teflon in a patient in whom a number of previous attempts had failed. Although the study showed the feasibility and timeliness of intraoperative monitoring of phonosurgery under general anesthesia, mechanical adduction of the vocal folds, rather than by stimulation of the laryngeal muscles, makes this method less than ideal.

The belief that surgeons would someday benefit by an ability to objectively determine the vocal fold's elastic properties prompted development of a simple device to measure Young's modulus in vivo.

METHODS

A prototype device[4] was modified for use with humans. This second device (Fig. 1) has a contact area of 6 mm^2 and has been preliminarily tested on four patients during surgery. The device was used during suspension laryngoscopy with a small endotracheal tube through an unmodified Dedo laryngoscope. Early in vivo canine experimentation has shown that, unless the thyroid cartilage was stabilized, the larynx itself could move. Preliminary studies with the device in humans have shown that suspending the larynx with a laryngoscope stabilizes the thyroid cartilage and prevents this from occurring. The 6 mm^2 plate (as presently designed) is placed at the mid one third of the vocal fold since the boundaries of the anterior commissure and vocal processes could produce unwanted stress-strain effects. Use of the device in humans posed a number of technological concerns important to the success of this project. Logis-

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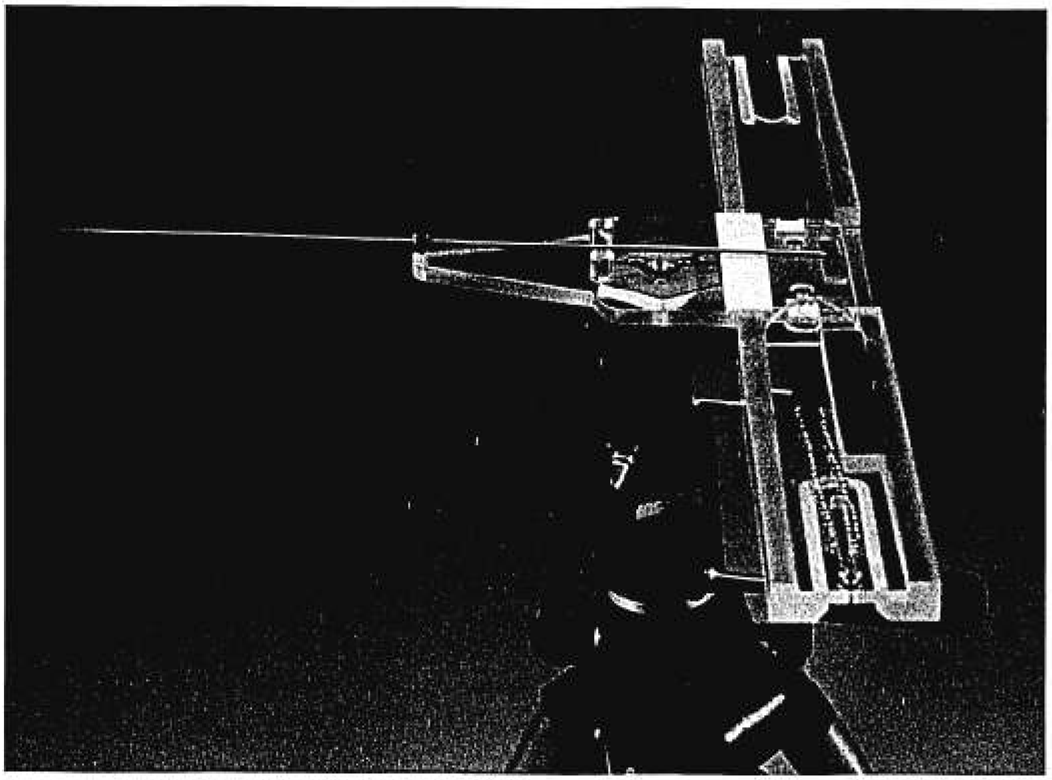

Fig. 1. Photograph of revised human prototype device to measure Young's modulus.

tically, in vivo measurement of the elastic modulus requires access to the vocal folds. A number of hospitals presently use No. 4 and No. 5 extra-long pediatric endotracheal tubes called "microlaryngoscopy tubes," which sit primarily in the posterior commissure of the vocal folds and permit free access to the vocal fold tissue. In addition, anesthesiologists are trained in jet ventilation techniques. These techniques have the advantage that virtually nothing in the laryngeal lumen obstructs the vocal folds.

Vocal Function Testing

Subjects completed the following voice recording protocols before and after laryngeal surgery. The pretest occurred within 2 weeks prior to surgery. Patients were retested 6 weeks after surgery.

Each recording session lasted approximately 45 minutes. The subjects were seated in a sound-treated room during recording. Tape recordings were made of all subject-generated signals using a high-fidelity AM tape recorder (Revox-MKII) for audio signals and an instrumentation PCM recording system (Instrutech VR100) for other signals. In addition, signals produced were simultaneously digitized.

Acoustic measures. The subjects wore a head-mounted microphone (Telex, Model 2021) positioned 10 cm from the mouth, at approximately 45 degrees azimuth. For acoustic recording that required the use of the pneumotachographic mask (during airflow recording), a cantilever-mounted microphone (Sony ECM 150T) positioned 5 cm in front of the mask was used. The audio signal was amplified, low-pass filtered by an 8-pole Butterworth filter at a 10-kHz corner frequency, and digitized at 40,000 samples per second with 21-bit quantization.

Each subject sustained the vowel /*a*/ at a comfortable pitch and conversational level of loudness as long and as steadily as possible. Assistance in maintaining a constant level of loudness was provided by the meter display on a microphone measuring amplifier (B&K, Type 2609). Three replications of this maneuver were digitized and 1 second of the middle portion of the longest production was used in the later analysis.

In the time domain, percentage of jitter and mean shimmer were measured by hand marking. These measures have been used in many speech laboratories for over a decade and have appeared as important measures in many published reports.[5–7] Jitter was calculated using parabolic interpolation for peak-marked data and linear interpolation when zero-crossing is marked.[8] Harmonics-to-noise ratio (H:N), which was highly related to noise ratings in spectrograms and useful in assessing results for treatment of hoarseness, was also measured.[9] The computation involved comparison of the energy of the averaged wave form to the energy of the differences between the pitch periods and the averaged wave form. Because the presence of jitter in the signal contributed to the H:N ratio, this measure was related to the jitter measure discussed previously. Finally, the "partial period comparison" described by Ladefoged and associates was calculated.[10] This measure is a time-domain comparison of the standard deviations of differences between moving vectors (portions of the acoustic signal), each about 0.6 times the estimated period length. A previous study[11] showed that this measure correlates well with ratings of vocal roughness.

In the frequency domain, measures of the amplitudes of various parts of a spectrum have also been used to characterize abnormal voice quality. One such measure, the difference between the fundamental frequency (F0) and the second harmonic (H2) (known as H1-H2) distinguishes among modal and breathy phonation types in spoken Hmong[12] and correlates with aerodynamic differences observed in other languages.[13] This measure has also been associated with breathy voice quality in patients with voice disorders.[11] All of the aforementioned acoustic measures were generated automatically.

Aerodynamic measures. Measurement of oral airflow and oral air pressure was performed in a manner similar to that described by Netsell, *et al.*[14] These measures, with the addition of the acoustic signal, were used to calculate vocal-tract resistance. Netsell, *et al.*[14] found measures of estimated subglottal pressure and vocal-tract airflow useful in assessing patients with various types of voice disorders. In addition, they found that listener evaluations were associated with particular airflow and air pressure characteristics.

Oral airflow was transduced by a differential pressure transducer (Glottal Enterprises MTW-1C) connected to a pneumotachographic mask (Glottal Enterprises, MA-1) described by Rothenberg.[15] Intraoral air pressure was sensed by a small diameter catheter (Medical Measurements 16 CT/S) placed through a port in the mask and positioned behind the lips. Six sequential productions of */ipi/* were produced. Two different sequential */ipi/* trials were digitized for each subject. In some subjects with severe glottal incompetence, as many productions as possible during one expiration were accepted. The peak intraoral pressure obtained during the */p/* closure served to estimate subglottal pressure. Oral airflow was measured at the midpoint of the preceding vowel. By applying the aerodynamic version of Ohm's law, vocal-tract resistance was calculated as the ratio of subglottal pressure to oral airflow.

Glottographic measures. Electroglottography (EGG) reflects the change in vocal fold contact area during phonation. Photoglottography (PGG) provides information regarding change in glottal area while the vocal folds were apart during the glottal cycle. Used together, these two measures provided complimentary information about vocal fold movement during phonation.

Each subject produced the vowel */i/* at comfortable and normal conversational loudness. The subject was instructed to sustain the vowel as long, steadily, and clearly as possible. This vowel was selected because it caused the epiglottis to be positioned anteriorly and provided less obstruction of the supraglottal illumination used for PGG. Light was projected into the oral cavity via a small diameter, high-intensity battery-operated flashlight inserted 2 to 3 cm beyond the teeth. The light was directed toward the soft palate and was reflected onto and through the glottis. A photosensor (Centronic OSD 50-2 in a custom-designed circuit and housing) was held in place by the experimenter over the neck in the vicinity of the cricothyroid membrane. This transoral approach provided PGG signals comparable to those recorded using a transnasal fiberoptic technique, but was less invasive and could be performed without the need of a physician.[6] The dry surface electrodes for the EGG were placed around the subject's neck and secured by a flexible Velcro band. Both the PGG light source and the EGG electrodes were positioned to maximize EGG and PGG signal amplitude on an oscilloscope prior to data collection.

The EGG, PGG, and the audio signal were amplified, low-pass filtered with an 8-pole Butterworth filter at 3 kHz, and digitized synchronously at 20,000 samples per second. A 1-second sample from the middle of the longest production was analyzed. Mean speed quotient, which has been used in the study of frame-by-frame vocal fold movements from high-speed film, was measured. Traditionally, speed quotient represents the duration that the glottis is open during the vocal cycle, divided by the duration the glottis is closed. Speed quotient was measured in the following manner. The most closed portion of each glottal cycle was first defined as 0% open or 100% closed, and then the duration from 10% open to peak opening was divided by the duration from peak opening to 90% closed. This method increased the ease of computation. In addition, speed-quotient results using this method correlated very highly ($r = 0.97$) with speed quotients derived from hand-marked points using the peak in the third derivative for locating first moments of opening and closing as previously described.[6]

Videostroboscopy. Videostroboscopy is a practical technique which overcomes the technical difficulties involved in high-speed filming but provides reliable information about vocal fold movement. Stroboscopy samples vocal fold images at time intervals that are correlated to the fundamental frequency, yielding an optical illusion that the vocal fold motion is slowed or stopped. Various aspects of vocal fold movement can then be judged from the recorded video signal.[16,17] However, because the image is a composite of portions of different glottal cycles, interpretation of the moving image must be made with some caution.

Stroboscopy was performed using a 90-degree telescope (Wolf dual channel, model 4452.57 or Nagashima, Type SFT-1) attached to a miniature endoscopic video camera (Jed Med CCD camera, model 70-5110) and a stroboscopic unit (B&K, model 4914). The video image was recorded on a ¾-inch video tape recorder (Sony VO 5800). Each subject was asked to sustain a production of */i/* at a comfortable pitch and loudness. This vowel was chosen to provide an unobstructed view of the glottis. Judgments were made by reviewing the videotape. Use of the variable speed, slow-and-stop scan available on the VCR allowed careful study of pertinent segments to increase accuracy of judgments.

Two measures (after Hirano[16]) of vocal fold movement and configuration, glottal closure and mucosal wave, were derived from the mean of ratings 1 through 5. The extent of glottal closure that occurs during the most closed portion in the glottal cycle was rated as follows:

1. Absent: No closure along the medial edges of the vocal folds is observed.

2. Severely incomplete: Some closure but less than one third of the medial edges of the vocal folds close against each other. Greater than two thirds but less than the entire medial edges of the vocal folds do not close against each other.

3. Moderately incomplete: More than one third but less than two thirds of the medial edges of the vocal folds close against each other.

4. Mildly incomplete: Less than complete closure but more than two thirds of the medial edges of the vocal folds against each other.

5. Complete: The entire medial edges of the vocal folds close against each other.

The size of the mucosal (traveling) wave visualized on the surface of the affected vocal fold was rated as follows:

1. Absent: No wave is observed.

2. Severely restricted: The wave is limited to the most medial edge of the vocal fold.

3. Moderately restricted: The wave moves laterally up to one quarter of the width of the vocal fold.

4. Mildly restricted: The wave moves more than one quarter but less than one half of the width of the vocal fold.

5. No restriction: The wave moves more than one half of the width of the vocal fold.

Because subjective evaluation of stroboscopy is prone to error, quantitative evaluation of videostroboscopic images through computerized analysis of digitized images is also being employed. The videostroboscopic images were quantitatively evaluated for degree of glottic closure. Recorded productions of /i/ were searched at jog and shuttle speeds to determine which fields represented the most closed and most open portions of a vibratory cycle. This technique has previously confirmed this representation by experience with correlating stroboscopic images to glottographic points of maximum opening and closure. It has been shown that, within a montage of stroboscopic images, the most open and most closed are easily identifiable.[18] The selected images were then transferred to a SONY UP-5000 Mavigraph video printer from the VCR's pause mode. The images were then digitized using a Data Translation DT 2853 frame grabber and Image-Pro software. The Mavigraph is required to freeze images from the VCR's pause mode without loss of resolution resulting from an unstable image. Also, the Mavigraph permits digitization of an individual video field, a necessity for subsequent area analysis. The digitized vocal fold images were then normalized. This was accomplished by transferring the anterior to posterior extent (from the anterior to posterior commissure) of a vocal fold image into a "box" of predetermined dimension, in effect making each vocal fold the same relative size. Glottal area was measured in pixels using a "free form" outline as shown in the stroboscopic images on the left side of Figure 2 (top). Three glottal area ratios were calculated from relative pixel areas: presurgery most closed to most open; postsurgery most closed to most open; and presurgery most closed to postsurgery most closed.

The symmetry of vocal fold excursion was also quantified using the symmetry ratio and normal/paralyzed (N/P) condition as described subsequently. This can also be obtained by using the digitized most open and most closed images. The single image on the right of Figure 2 (top) depicts this procedure. A composite image is created from the most open and most closed images in the same phonatory sample at the level of maximum glottic width. The composite image is then normalized (left insert) and the length of vocal fold lateral excursion from most closed to most open is measured on each side in pixels. In order to compare ratios between patients with either left or right paralyses, the vocal cord with greater excursion is always designated as "a" and is placed in the numerator. A second variable is then used to indicate whether the normal "N" or paralyzed "P" cord demonstrates the greatest lateral excursion.

RESULTS

As an ongoing part of this research, the utility of measuring the elastic properties of the vocal fold is being evaluated. Thus, an important aspect of the research undertaken is the multidimensional analysis of vocal function before and after surgery. The following case history demonstrates this approach. Figure 2 and Table I display vocal function studies before and after surgery for a 30-year-old attorney (patient 1) who presented with a problem of weakening in his voice that made it difficult for him to raise his vocal loudness in the court room. For comparison, Table I includes the 95% confidence interval for normal individuals of the same sex and age range as the patient. Examination with a mirror showed left cord paresis. However, a glottographic examination showed a change in speed quotient to a value less than 1.0. This change in speed quotient has been associated with flaccid, unilateral asymmetry of the vocal folds.[18] In addition, preoperative vocal function studies demonstrated a lower than normal glottal resistance. His work-up showed the laryngeal problem to be an idiopathic lesion. Stroboscopic examination demonstrated that the glottis was incompetent with an absent left mucosal wave. The right, unaffected, vocal fold had less excursion from the midline than normal due to lack of subglottic pressure buildup beneath the cords.

TABLE I.
Measures Before and After Surgery for Patient 1.

Measure	Observed Values Before Surgery	Observed Values After Surgery	Normal Range (95% Confidence Interval, n = 10)
Percent jitter	0.418	0.673	0.307–0.457
Mean shimmer (dB)	0.396	0.180	0.225–0.391
Harmonics-to-noise (dB)	25.87	29.51	24.75–34.15
Partial period comparison	0.109	0.148	0.079–0.107
H1-H2 (dB)	8.82	−3.45	1.77–5.76
Speed quotient	0.70	1.22	1.02–1.44
Shift quotient	0.25	0.5	0.5–0.6
Open quotient	0.8	0.5	0.50–0.67
Subglottal pressure (cm H_2O)	7.6	7.3	6.0–9.8
Airflow (LPS)	0.356	0.355	0.128–0.239
Glottal Resistance (cm H_2O/LPS)	21.3	20.6	38.2–71.8

The patient underwent a type I thyroplasty medialization procedure under local anesthesia. The procedure was complicated by the patient's inability to phonate in his normal low-pitch range. The difficulty was probably a result of loss of proprioception resulting from the local anesthetics, which led to adjustment of his vocal folds at a higher stiffness and pitch range than he preferred. However, despite the fact that his vocal pitch in connected speech was higher than he preferred postoperatively, there was return of the traveling wave motion stroboscopically. Figure 2 (left side of top figure) demonstrates the computerized-analysis technique comparing relative glottic area in patient 1 before and after type I thyroplasty, during the most closed and most open segments of the

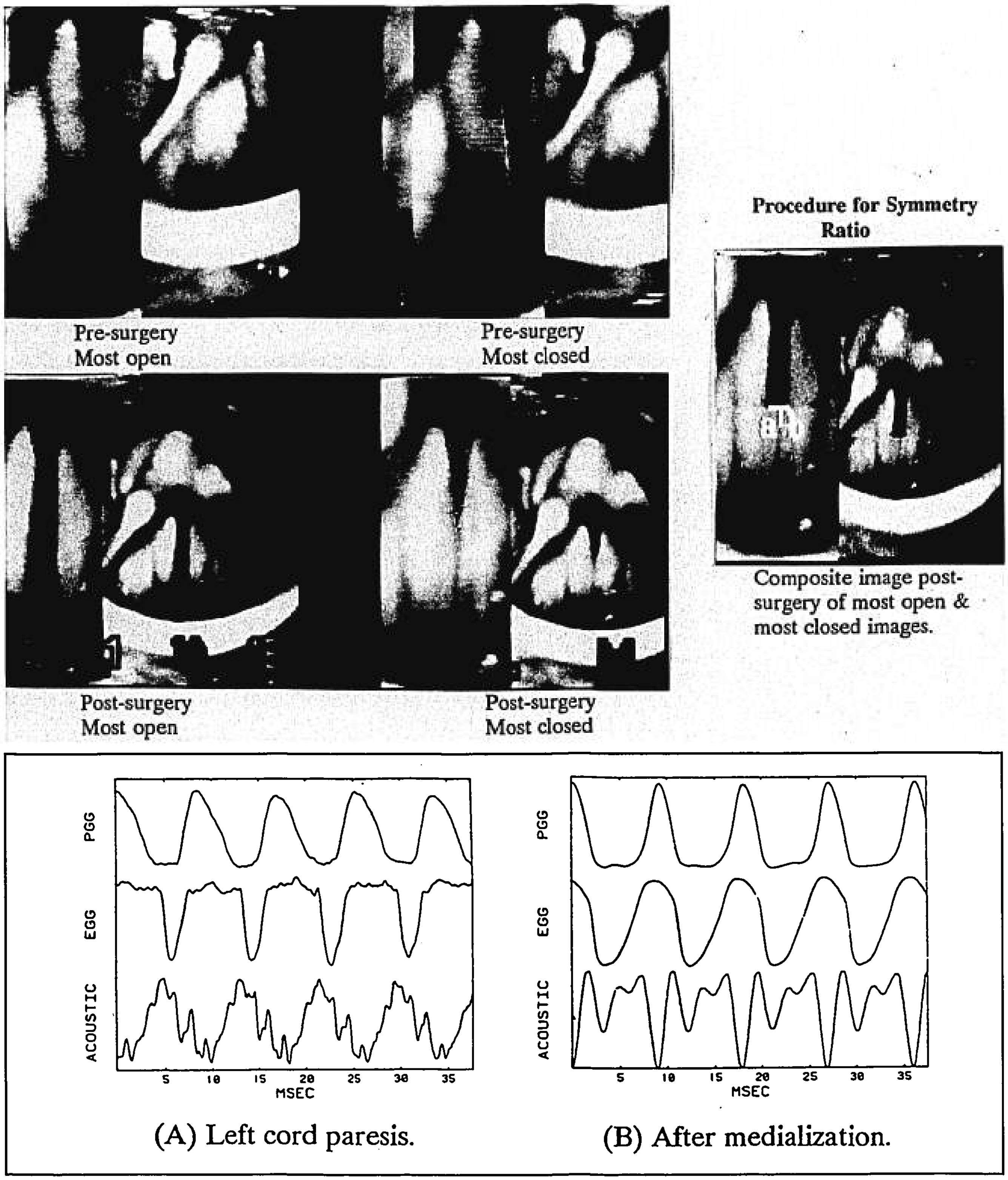

Fig. 2. **Top.** Objective measurement of videostroboscopy image of patient 1 before and after type I thyroplasty. **Bottom.** Glottographic waveforms of patient 1 before and after type I thyroplasty.

cycle. The measurements were made from digitized stroboscopic images after normalizing the anterior-to-posterior vocal fold lengths as shown in the left side inserts. For this patient, preoperatively, the most closed to most open area ratio is 6,302:13,191 pixels, or 0.47; postoperatively the area ratio is 3,317:11,357 pixels, or 0.29. In comparison, the ratio is zero in the normal case in which there is no glottal gap during

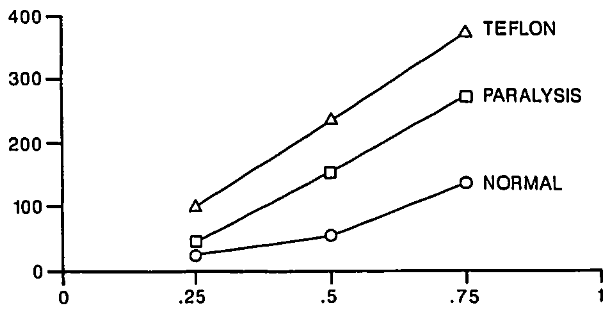

Fig. 3. Stress *vs.* strain plot for patient 2 for normal, paralyzed, and Teflon injected vocal cords.

the most closed portion of the cycle. Also, the postoperative to preoperative most closed area ratio is 3,317:6,302 pixels, or 0.52. This indicates that the surgery reduced the glottal gap during the most closed portion of the cycle by 52%. However, postoperatively there was still a glottal gap during the most closed portion of the vocal cycle: the patient's most closed area was still 29% of the most open area.

Analysis of traveling wave symmetry is also depicted in the right side of Figure 2 (top) after thyroplasty type I surgery. The vocal folds meet during closure, so that the maximal excursion is length "a" on the patient's right and length "b" on the left. In this case, a = 15.0 pixels, and b = 13.1 pixels. The a:b symmetry ratio is 1.1, indicating that the vibration is symmetric. In contrast, preoperatively, the symmetry ratio of patient 1 was 26.0 pixels/10.1 pixels, or 2.6. This indicates that the right unaffected cord's excursion was over 2.5 times greater than the left cord's excursion.

There was a return to normal values of speed, open, and shift quotient as demonstrated glottographically in Figure 2 (bottom). Acoustically, his voice showed an improvement in the difference between the fundamental frequency and second harmonic (H1-H2). He continued to demonstrate lower than normal laryngeal resistance, because medialization laryngoplasty cannot effectively close a posterior glottic gap. However, because the patient's voice sounded better perceptually, this patient's surgery probably would have been simply categorized as a good result. It is only through more objective evaluation that a full picture of this patient's vocal function can be represented. Furthermore, a better understanding of this patient's vocal fold moduli would have permitted a more intelligent adjustment intraoperatively.

The first patient to have intraoperative modulus measurements was a 72-year-old man (patient 2) who

TABLE II.
Measures Before and After Surgery for Patient 2.

Measure	Observed Values Before Surgery	Observed Values After Surgery	Normal Range (95% Confidence Interval, n = 10)
Percent jitter	1.536	0.665	0.291–0.786
Mean shimmer (dB)	0.804	0.717	0.230–0.639
Harmonics-to-noise (dB)	17.33	20.62	19.88–33.37
Partial period comparison	0.329	0.299	0.086–0.212
H1-H2 (dB)	25.19	8.11	−7.40–9.45
Speed quotient	0.69	0.91	0.92–1.40
Subglottal pressure (cm H_2O)	21.5	14.5	5.5–11.3
Airflow (LPS)	1.291	0.344	0.128–0.254
Glottal resistance (cm H_2O/LPS)	16.7	42.2	29.6–54.4

underwent Teflon injection for chronic cord paralysis. This device was used intraoperatively to measure the elastic modulus of his normal and affected vocal folds. The modulus of the affected cord was also measured after Teflon injection. Interestingly, the atrophied cord had a higher resting stress than the normal cord for all levels of strain, as shown in Figure 3. Also, differences between the normal and paralyzed values became more pronounced as strain increased. The higher modulus for the paralyzed cord is probably related to progressive atrophy of a vocalis muscle having a lower elastic modulus, and its replacement with fibrous tissue having a higher modulus value. Furthermore, one might expect different moduli for acute compared to chronic paralyses. Some of the variability between patients, reported for vibration of paralyzed cords, may relate to ongoing atrophy and the associated change in the vocal fold's modulus with time. In addition to compensation by the normal cord, improvement in vocal function may occur because of increasing stiffness in the affected fold with time. This increased stiffness would more closely approximate the vocal fold stiffness produced during normal phonation. Injection of Teflon in this patient increased the modulus to 4.0×10^5 dynes/cm^2 at 25% maximal strain, an increase of nearly 400% over the resting normal fold. This value is also considerably larger than the in vivo canine model values for Teflon injection. Although a number of factors account for this canine-human difference, this disparity probably results from the larger proportion of loose connective tissue in the canine vocal fold compared to that in the human.

Postoperatively the patient exhibited marked improvement of acoustic, glottographic, and aerodynamic measures as demonstrated in Table II. Stroboscopically, glottal closure changed from severely incomplete before surgery to only mildly incomplete after surgery. His mucosal wave, absent before surgery on the paralyzed cord, was mildly restricted after surgery. Quantitative stroboscopic evaluation revealed a preoperative to postoperative most closed

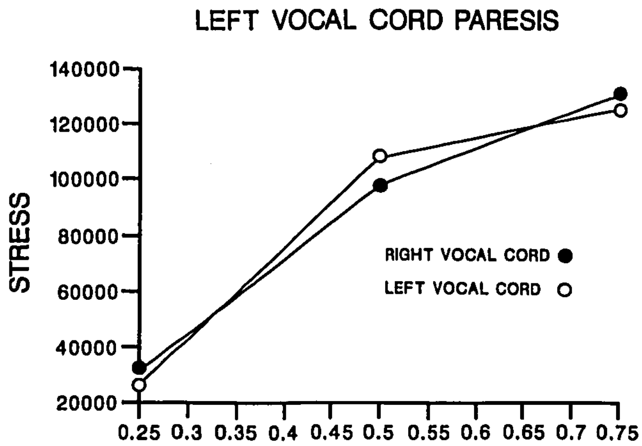

Fig. 4. Stress *vs.* strain plot for patient 3 with a left vocal cord paresis.

TABLE III.
Measures Before and After Surgery for Patient 3.

Measure	Observed Values Before Surgery	Observed Values After Surgery	Normal Range (95% Confidence Interval, n = 10)
Percent jitter	1.965	0.797	0.309–0.467
Mean shimmer (dB)	1.088	0.545	0.229–0.397
Harmonics-to-noise (dB)	0.83	20.21	19.24–24.03
Partial period comparison	0.460	0.246	0.079–0.128
H1-H2 (dB)	10.22	12.52	3.53–7.79
Speed quotient	1.06	NA	1.08–1.53
Subglottal pressure (cm H_2O)	8.9	5.9	5.5–8.0
Airflow (LPS)	0.844	0.275	0.097–0.145
Glottal resistance (cm H_2O/LPS)	10.5	21.6	39.4–75.6

to most open area ratio change from 45% to 11%, respectively. Also, the symmetry ratio similarly improved from 2.3N to 1.2N. These results demonstrated that improvement in vocal function in this patient was associated with an increase in the elastic modulus of his paralyzed cord caused by Teflon augmentation.

The next patient to undergo modulus measurement was a 61-year-old woman (patient 3) who had presented with severe unilateral, left paralysis/paresis and a large posterior glottal gap. However, unlike the previous patient, her resting moduli were essentially the same for both vocal folds, as shown in Figure 4. Direct laryngoscopy failed to demonstrate the atrophy typically observed in long-standing paralysis. Based on these findings, a decision was made not to inject the fold with Teflon because augmentation is contraindicated in paresis states. The patient instead underwent an arytenoid adduction procedure to medialize the left vocal process. At the fifth postoperative day, her vocal function was reexamined as shown in Table III. Even in the early recuperative period, her acoustic and aerodynamic measures had improved. Stroboscopically, she changed from having a severely incomplete glottal closure before surgery with no mucosal wave observed in the affected cord, to mildly incomplete closure with only mild restriction of the mucosal wave after surgery. Her most closed to most open area ratio went from 46% preoperatively to 10% postoperatively. The postoperative to preoperative most closed area ratio was 87%. The symmetry ratio changed from 3.4N to 1.3N. The stroboscopic analysis indicated that arytenoid adduction closed the glottic gap quite effectively and improved traveling wave symmetry. Further, this case demonstrated the device's potential in assessing laryngeal states of paralysis and paresis.

A 47-year-old man (patient 4) had undergone direct stimulation of the laryngeal nerves while his elastic modulus was measured during parathyroid surgery for hypercalcemia. He was known to have a left recurrent paralysis, possibly caused by cricoarytenoid fixation secondary to the severe disorder. However, at surgery the arytenoids appeared quite mobile. The right cord showed a secant modulus of 1×10^5 dynes/cm^2 at 50% strain. His left paralyzed cord modulus was 2.8×10^5 dynes/cm^2. The recurrent laryngeal nerve stimulator was applied directly to the dissected nerves. The left cord was found to be paralyzed. However, the right nerve stimulated the right cord effectively, indicating that the patient could be extubated successfully. Movement was first noted at a current stimulus of 0.2 mA (frequency 90 Hz, duration 1.5 msec). Maximal stimulation, noted by arytenoid adduction and vocalis bulging, occurred at 0.6 mA. Intermediate stimulation at 0.4 mA produced a measured secant modulus of 7.5×10^5 dynes/cm^2 at 50% strain. This is the first reported data for a human in vivo transverse vocal fold modulus during recurrent laryngeal nerve stimulation, and demonstrates that vocalis contraction significantly affects the modulus.

The last patient was a 55-year-old woman (patient 5) who underwent transtracheal recurrent laryngeal nerve stimulation and elastic modulus measurement. She had been involved in a motor vehicle accident in 1982 and had sustained injury to her laryngeal nerves during an emergency tracheostomy. She also experienced a head injury with neuromotor sequellae including dysarthria. In an effort to improve her voice, the patient underwent a right vocal cord Teflon injection (for presumed paralysis) 2 years after the accident. On initial presentation, 5 years after injection, she appeared to have only a 3-mm glottis during respiration and was severely breathy and hoarse on phonation. Despite an attempt at phonatory evaluation, an accurate picture of her laryngeal function was obscured by distorted laryngeal anatomy. Glottographic and acoustic analysis of the patient's phonatory productions were complicated by severely aperiodic signals. A decision was made to perform diagnostic endoscopy, but because of her compromised airway, the patient underwent a temporary tracheostomy during suspension laryngoscopy. At surgery, a modified armored tube, fitted with cuff electrodes, was used to transtracheally stimulate her laryngeal nerves. Although Teflon had been injected into the right vocal cord, transtracheal stimulation demonstrated that the left vocal cord was paralyzed. The elastic modulus of the left cord was 2.2×10^5 dynes/cm^2 at 50% strain, indicating a chronic paralysis.

Transtracheal electrical stimulation at 20 mA of current, 1 msec pulse duration and 80 Hz produced incomplete adduction of the right vocal cord, indicating that it was mobile, but paretic. Insufflation of a rostrally directed humidified airflow into the trachea during electrical stimulation demonstrated that neither cord vibrated normally to produce phonation. Measurement of the elastic modulus of the right cord during electrical stimulation was 5×10^6 dynes/cm^2 at 50% strain, indicating that the elastic modulus was tenfold higher than expected for normal vocalis contraction. A biopsy confirmed the suspicion of a right vocal cord Teflon granuloma, accounting for the abnormally high modulus. After unsuccessfully attempting to remove the granuloma endoscopically, the right vocal cord was reconstructed with the right false cord, taking care to maintain the integrity of the arytenoid cartilage as well as the lateral and posterior cricoarytenoid muscles. Postoperatively, she was decannulated and regained use of her voice. Knowledge of this patient's elastic moduli and extent of vocal cord mobility was essential in making the correct diagnosis and formulating an appropriate treatment plan.

DISCUSSION

Based on a comparison of patient 4's resting-to-nervous stimulation moduli and the in vivo[4] canine results, one can hypothesize that during some modes of vocal fold vibration, the stiffness of the vocalis is of an order of magnitude higher than the mucosal stiffness, such that the system acts much like fluid flowing through a collapsible tube. In this case, the significantly higher stiffness of the tube or vocalis determines the effective elastic properties of the fluid or mucosa.[19] This notion is in keeping with the theory that vibration occurs primarily in the mucosa, and emphasizes the necessity of an intact lamina propria for normal voicing. As the elastic modulus of the vocal fold increases due to external cricothyroid stretching or internal vocalis stiffening, the velocity of the traveling wave increases in conjunction with an increase in pitch.

Every otolaryngologist who has endoscopically palpated a vocal fold with a Teflon granuloma or an invasive carcinoma has a qualitative notion of how histologic lesions may affect the elastic modulus of the vocal fold. However, even in the absence of histologic lesions affecting the folds, abnormal phonation can result simply from stiffness imbalances between the left and right vocal cords or from abnormally high symmetric stiffnesses. For example, some patients exhibit laryngeal paresis states in which, stroboscopically, the paretic cord, although mobile, appears floppy. This results from loss of internal vocalis contractility or extrinsic cricothyroid tension. Typically, despite asymmetric stiffness, entrainment of the right and left vocal folds occurs through tissue proximity and airflow. Because of entrainment, patients with pareses usually experience only modest reductions in vocal efficiency and mild abnormalities in acoustic measures. However, when asymmetric stiffness conditions are associated with decoupling due to wide glottal gaps, the left and right traveling wavespeeds may diverge, producing serious aberrations in vibration and acoustics.

In contrast to asymmetric flaccid laryngeal states, another group of patients demonstrate hyperfunctional voice disorders. These occur when the normal neuromuscular reflex loops controlling intralaryngeal medial adductory compression are disturbed, resulting in a mismatch between the glottal resistance, which must be overcome to initiate phonation, and the pulmonary driving pressure. Because glottal resistance is primarily determined by vocalis stiffness,[20] modification the vocal fold's elastic modulus is the key to successfully treating hyperfunctional laryngeal voice disorders. Thus, cognizance of the role the elastic modulus plays in determining normal and pathologic phonation is one of the first steps toward designing new phonosurgical procedures to alter voice and correctly administering the current ones. Furthermore, improved voices should result when reconstruction of the larynx following extirpative cancer surgery or trauma takes into consideration the viscoelastic attributes of the neocords created. This should include a layered structure of a mucous membrane with an underlying muscle capable of altering its elastic modulus.

As additional knowledge concerning the essential elements needed for oscillation is accumulated, it is not inconceivable that, in the near future, a biologically fabricated neolarynx preserving both respiratory function and phonation could be offered to selected patients. If these recommendations seem implausible at first, the reader is reminded that physiologic vibration of the air stream is not unique to the larynx. Examples can be found all the way from the "Bronx cheer" to esophageal speech. A number of researchers believe that these forms of physiologic vibration are just a specific subset of oscillation in collapsible tubes.[21] In this analogy, the external pressure acting on the collapsible tube is comparable to the active muscle tone of the vocal cords tending to produce closure. A prosthetic vocal source has also been developed using a collapsible tube as a fluid mechanical oscillator.[22] Although the physics are not fully understood, collapsible tubes seem to oscillate when the proper relationship occurs between the internal and external tube pressures and the elastic modulus of the tube itself.[21,24] Application of collapsible tube physics to biological engineering of neolarynges will require a detailed understanding of the viscoelastic properties of the human vocal folds. This should be the subject of future investigation.

Further modification of the device will take place to permit connection to the handle of the laryngoscope. A small platform will be mounted to the laryngoscope's handle. The "deflection" bar will hang below the platform and enter the laryngoscope. A force transducer will determine the force required to displace a small plate contacting the fold a measured distance. It is anticipated that, in practical applications, only one stress at 50% strain (2-mm displacement, assuming horizontal thickness of 4 mm) will be obtained intraoperatively.

CONCLUSIONS

1. In states of laryngeal paralysis, both Teflon augmentation and progressive fibrosis increase the elastic modulus of the vocal fold.

2. The transverse elastic modulus of the vocal fold can be measured intraoperatively and may be useful in diagnosing and surgically treating laryngeal disorders.

3. A multidimensional analysis of voice is important when evaluating the effects of surgery on laryngeal vibration and vocal quality.

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